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(54) Title: FUSION APPARATUS

(57) Abstract

Fusion apparatuses for coupling fusible material to a quantized mode to result in coherent fusion are provided. Method for optimization of reactor operation, control of the coherent fusion reaction and extraction of usable energy generated are provided.

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FUSION APPARATUS

Background of the Invention

This application is a continuation-in-part of application USSN 335,751 filed April 10, 1989 by Peter L. Hagelstein entitled "Fusion Apparatus".

This invention relates to cold fusion apparatus.

Fleischmann and Pons have asserted that heat produced by electrolytically deuterium-loaded palladium rods results from near room temperature nuclear fusion (Fleischmann and Pons, J. Electroanalytic Chemistry, 261, 301 (1989); Petrasso, et al., Nature 339, 183 (1989); Fleischmann, et al., Nature 339, 667 (1989); Petrasso, et al., Nature 339, 667 (1989)).

"Cold fusion" effects have been reported in a number of electrolysis experiments (Jones, et al., Nature 339, 737 (1989); R. Huggins, presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989; Gozzi, et al., presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989; Srinivasan, et al., presented at the Workshop on Cold Fusion Phenomena at Sante Fe, May 1989; Bertin, et al., presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989; Wolf, et al., presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989) and in gas cells (De Ninno, et al., Europhysics Letters 9, 221 (1989); De Ninno, et al., presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989; experiments of Magini et al. and of Mazzone et al. of ENEA at Casaccia, discussed by Scaramuzzi at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989; Menlove, et al., presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989).

Other efforts to detect evidence of cold fusion have yielded negative results. (Gai, et al., Nature 340, 29 (1989); Hsuan, et al., presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989; Lewis and Barnes, presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989; Ziegler, et al., Phys. Rev. Lett., 62, 2929 (1989); Albagli, et al., Workshop on Cold Fusion Proceedings to appear in J. Fusion Energy (1989)).

Efforts have been directed towards identifying the mechanism responsible for cold fusion effects (Lipson, et al., Sov. Tech. Phys. Lett., 12, 551 (1989); Rafelski, et al., unpublished AZPH-TH/89-19 March 27, 1989, submitted to Nature; Garwin,

Nature 338, 616 (1989); Mayer, et al., presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989; Dickinson, et al., submitted to J. Mat. Res. (1989); Seitz, Nature 339, 185 (1989); Gajda, et al., presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989; Krapchev, unpublished; Cohen and Davies, Nature 338, 705; Richards, presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989; Sun and Tomanek, Phys. Rev. Lett., 63, 59 (1989); Koonin and Nauenberg, Nature, 339, 690 (1989) Tajima, et al., unpublished April 1989; Parmigiani and Sona, to appear in Il Nuovo Cimento (1989); Pharmawardana and Aers, submitted to Chem. Phys. Lett. (1989); Koonin, submitted to Phys. Rev. Lett., April 1989; Li, unpublished technical report, U. of Maryland, April 1989; Leggett and Baym, Phys. Rev. Lett, 63, 191 (1989); Leggett and Baym, Nature, 340, 45 (1989); Gryzinski, Nature, 338, 712 (1989); Johnson and Clougherty, to appear in Mod. Phys. Lett. B (1989); Guinan, et al., LLNL report 100881 (1989); Nazgamine, et al., presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989; Shibab-Eldin, et al., unpublished Lawrence Berkeley Laboratory, April 1989; Walling and Simons, unpublished U. of Utah, Chemistry Dept., April 1989; Irvine and Riley, Nature, 339, 515 (1968); W. Fowler, Nature, 339, 345 (1989); Danos, presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989).

Summary of the Invention

The coherent fusion apparatus of the invention includes a source of fusible material, for example deuterium, and a means for exciting that material to initiate and sustain coherent fusion. It further includes a means for monitoring the rate of the coherent fusion reaction such as a neutron or α-particle detector, and a means for extracting usable energy from the coherent fusion apparatus.

According to another aspect of the invention, fusible material is coupled to a quantized mode which may be a mechanical, electrical, magnetic, or composite mode so that this coupling is sufficiently strong to effect the onset of coherent fusion. In a preferred embodiment, fusible material is contained within an electrically conductive, radially symmetric containment vessel and coherent fusion is initiated through coupling to plasmon modes. In other embodiments, fusible material is contained within insulating vessels where coupling is accomplished by radially polarizing insulating crystals.

According to another aspect of the invention, the cosmic ray permeable fusion apparatus includes fusible material contained within an electrically conductive containment vessel provided with radially disposed rod-like projections electrically connected in series with an oscillator and in series or parallel with a computer-controlled variable load to extract energy from the coherent fusion process. An electrically excited coherent fusion apparatus may be coupled electrically to a load either in series or in parallel. This means of electric energy coupling may be tuned further by the insertion of a variable resistance element in these circuits.

In a preferred embodiment, the oscillator includes a variable quality factor (Q) resonator for acoustical excitation of fusible material, including hydrogen and deuterium in proportions adjusted for optimization of the coherent fusion rate. An α-particle source may also be provided to initiate coherent fusion. The vessel preferably consists of metal resistant to enhanced fission.

In another aspect of the invention, the fusion apparatus includes fusible material within an insulating containment vessel surrounded by radially disposed polarizable crystals and apparatus for extracting usable energy produced by the coherent fusion process.

In preferred embodiments of insulating containment vessel fusion apparatus, fusible material includes hydrogen and deuterium in proportions adjusted to optimize the coherent fusion rate. The coherent fusion process is stopped by selective introduction of a proton excess. Also, the vessel consists of low atomic number material, such as lithium hydride and is thin-walled. Usable energy can be extracted with a metal positron trap and heat built up within the apparatus may be removed by embedded, thermally conductive mesh. The vessel can be cosmic ray permeable and can include an α-particle source for fusion initiation.

All fusion apparatus can accommodate various radially symmetric geometry containment vessels including cylindrical, spherical, or toroidal geometries, use of gaseous, liquid, solid, or cryogenic fusible material including solids such as ice or metal hydrides and removal of by-products of the coherent fusion process such as tritium using a circulation loop. A selectively permeable membrane such as gold-coated palladium may be used to adjust hydrogen/deuterium fusible material ratios.

According to another aspect of the invention, a neutron or α-particle detector may be combined with a coherent fusion apparatus to monitor the fusion rate.

Coherent fusion reactors can also be used to drive lasers either by creating a large

potential difference needed to excite a gas discharge laser or by direct coupling to electronic transition lasers including gases such as N_2, semiconductors such as GaAs or crystalline insulator laser hosts such as yttrium aluminium garnet (YAG).

A coherent fusion reactor may also be used to drive a vibrational transition laser or maser via direct or filtered energetic coupling.

The energy created in a coherent fusion apparatus can be used to promote a chemical reaction having a high activation barrier such as nitrate synthesis. This energy may also be utilized for transmutation of elements, generation of artificial isotopes, and processing of radioactive wastes to remove high atomic number radioactive isotopes.

Coherent deuterium fusion byproducts, ^3He and neutrons, may be harnessed for useful purposes. The ^3He may be contained for subsequent use in cryogenic studies and the neturons may be utilized for neutron spectroscopy.

Brief Description of the Drawing

In the drawing:

Fig. 1a is a schematic cross section of a fusion apparatus;

Fig. 1b is a schematic illustration of a fusion apparatus coupled in parallel to a load;

Fig. 1c is a schematic illustration of a fusion apparatus coupled to a load in parallel with a variable resistance element;

Fig. 2a is a schematic sideview of a fusion apparatus; and

Fig. 2b is a schematic endview of a fusion apparatus;

Fig. 3 is a schematic illustration of a fusion reaction rate monitoring system consisting of a neutron detector positioned near a fusion apparatus;

Fig. 4 is a schematic illustration of a fusion apparatus used to excite a discharge laser;

Fig. 5 is a schematic illustration of a fusion apparatus used to excite a semiconductor laser;

Fig. 6 is a schematic illustration of a fusion apparatus used to excite electronic transitions in a laser wherein energetic coupling occurs directly between the fusion apparatus and the laser material;

Figs. 7a and 7b are schematic illustrations of fusion apparatus used for promoting a chemical reaction;

Figs. 8a and 8b are schematic illustrations of fusion apparatus used for transmutation of an element;

Fig. 9 is a schematic illustration of a fusion apparatus used to generate neutrons for spectroscopy;

Fig. 10 is a schematic illustration of a fusion apparatus used to generate ^3He;

Fig. 11 is a schematic illustration of a fusion apparatus excited by an ion beam; and

Fig. 12 is a schematic illustration of an amplifier which includes a fusion apparatus.

Description of the Preferred Embodiment

A simple model for coherent fusion in the presence of a lattice has been developed. The model suggests that the reactions

$$p + d \longleftrightarrow {}^3He \rightarrow t + e^+ + v_e \tag{1}$$

$$d + d \longleftrightarrow {}^4He \rightarrow {}^3He + n \rightarrow t + p \tag{2}$$

$$p + t \longleftrightarrow {}^4He \rightarrow {}^4He + \gamma \tag{3}$$

can occur coherently via an electric monopole (EO) interaction with a lattice. These fusion reactions are accelerated if the magnitude of the interaction matrix element exceeds the geometric mean of the phonon energy and the nuclear energy, neglecting damping.

An alternative, exotic, three-body proton-deuterium reaction can occur in the presence of a lattice of X nucleons which becomes excited to a state, X^*, before alpha decaying to X' according to the reaction:

$$p + d + X \rightarrow {}^3He + X^* \rightarrow {}^3He + X' + \alpha - particle + energy \tag{4}$$

The excitation of palladium nucleii by 5.49 MeV leads to excited states for which fast alpha decay is a principal decay mode with neutron and proton emission energetically forbidden. The energies released are 3.38, 2.87, 2.59, 2.26, 1.64 and 1.06 MeV for palladium isotopes with A equal to 102, 104, 105, 106, 108, 110 respectively. This mechanism is not operative in titanium electrolysis cells.

A third class of reactions can proceed which produce virtual localized intermediate states according to the following reactions:

$$p + p \rightarrow ({}^2He)_V \rightarrow d + e^+ + \nu_e + 1.05MeV \tag{5}$$

$$d + t \longleftrightarrow ({}^5He)_V \rightarrow {}^4He + n \quad (6)$$

$$t + t \longleftrightarrow ({}^6He)_V \rightarrow {}^4He + 2n \quad (7)$$

where $({}^nHe)_V$ indicates localized continuum states which have maximum overlap with the final state products. Virtual fusion reactions leading to stable ${}^3He$ and ${}^4He$ isotopes are exothermic; additionally, $d + d \longleftrightarrow {}^4He^*$ can be an exothermic virtual path. The remaining virtual fusion reactions are endothermic.

The incoherent branches can be either fast decays if mediated by the strong force or electromagnetic force, or slow decays if mediated by the weak force. In the case of fast decay channels, only a small fractional virtual population needs to be established to obtain an observable decay rate. For the beta decay paths, a very large virtual population is required to produce an observable effect. A formulation is developed which applies to both classes of reactions.

The overall scenario which we are attempting to develop works as follows: a mixture of protons and deuterons are introduced into a lattice, react virtually, and decay. The proton-proton path in this scenario produces heat, and the proton-deuterium path produces tritium. Since the beta decay is slow, a substantial virtual helium population is required to obtain observable levels of heat or tritium. The build-up of the virtual helium population takes time to occur (and may not occur in every experimental set-up). The $({}^2He)_V$ decay to tritium takes about 200 sec. Thus, virtual $({}^2He)_V$ levels can be in the vicinity of 10^{16} for a several-watt system. Such a picture is qualitatively consistent with the experimental report of Pons and Fleischmann.

Coherent acceleration of the fusion rate requires that coupling proceed to a single final state, and that the process be reversible, i.e., matrix elements for the reverse process be equal to those for the forward reaction. Coherent processes which occur in a phonon laser are distinquished from those in a conventional laser in that no conventional laser exhibits an interaction energy exceeding the transition energy. The fundamental constraint for the onset of coherent fusion is given by Equation 8 where H represents a static Hamiltonian, ω_n is the nuclear angular frequency, ω_p is the phonon angular frequency, and $\hbar$ is Planck's constant/2π.

$$|\langle|\ H\ |\rangle| >> \sqrt{(\hbar\omega_n)(\hbar\omega_p)} \quad (8)$$

Energy produced from the interaction, fusion, of protons and deuterons couples to phonon modes. The rate of phonon generation when n nuclear fusions have occurred

in the lattice is given by Equation 9

$$\gamma_p = \frac{4}{\pi} \frac{|\ \langle |\ H\ | \rangle\ |^2}{\hbar^2 \omega_n} \tag{9}$$

where γ_p is the phonon generation rate. Energy conservation requires that ω_n/ω_p phonons be generated for each fusion event, yielding an associated fusion rate, γ_f, given by Equation 10.

$$\gamma_f = \frac{4}{\pi} \frac{\omega_f}{\omega_n^2} \left| \frac{\langle |\ H\ | \rangle}{\hbar} \right|^2 \tag{10}$$

When large numbers of nuclear fusions occur in the lattice, the phonon generation rate, γ_p, is given by Equation 11

$$\gamma_p = \frac{4\sqrt{2}}{\pi} \omega_p \left| \frac{\langle |\ H\ | \rangle}{\hbar \omega_n} \right|^2 \tag{11}$$

which is smaller than the result obtained in Equation 9 by a factor $\sqrt{2}\omega_p/\omega_n$.

The model may be extended to describe the coupling of the nuclear energy generated to multiple phonon modes. Such coupling is assumed to be dominated by transitions in which only a single phonon is exchanged. Equations 12 and 13 may be used to develop estimates of coherent fusion effects in macroscopic systems. The total phonon generation rate, γ_p, may be interpreted physically as being equal to the sum of the rates of each mode acting independently. The associated total fusion rate is given by Equation 13.

$$\gamma_p = \sum_j \frac{4}{\pi} \frac{|\ \langle 0, m_j\ |\ H\ |\ l, m_j + 1 \rangle\ |^2}{\hbar^2 \omega_n} \tag{12}$$

$$\gamma_f = \frac{4}{\pi} \frac{\omega_j}{\omega_n} \frac{|\ \langle 0, m_j\ |\ H\ |\ l, m_j + 1 \rangle\ |^2}{\hbar^2 \omega_n} \tag{13}$$

The fusion rate for a given mode is essentially zero unless the interaction is strong enough such that the coherent fusion constraint (Equation 8) is satisfied. The constrain is a statement that the phonon generation rate must exceed the phonon frequency for strong coherence to be achieved. We may use this constraint to examine the threshold condition for the lowest mode of a macroscopic coherent fusion system.

A bar with a lowest mode of frequency 1 kHz (corresponding to a phonon energy of 4×10^{-12} eV) requires an interaction matrix element of 5×10^{-3} eV to reach threshold

for the p+d $\rightarrow^3 He + 5.5MeV$ reaction. The fusion rate under these conditions is quite small (7 x $10^{-15} sec^{-1}$).

In order to obtain a coherent fusion rate which is sufficiently large to be measurable, we require a much larger interaction matrix element as well as the participation of numerous phonon modes. As a crude approximation, we might imagine the interaction matrix element to be nearly constant over the low energy phonon spectrum. If this is assumed, then the fusion rate becomes

$$\gamma_f = \frac{4}{\pi}\left[\frac{|\ \langle|\ H\ |\rangle\ |}{\hbar\omega_n}\right]^2 \sum_j \omega_j \tag{14}$$

The number of modes which are available at a phonon frequency ω_j is on the order of $3V\omega_j^2 d\omega_j/(2\pi c)^3$, where c is the sound speed and V is the volume involved. The sum can be approximated by an integral if the number of modes is large, giving

$$\gamma_f = \frac{4}{\pi}\left[\frac{|\ \langle|\ H\ |\rangle\ |}{\hbar\omega_n}\right]^2 \frac{3V}{(2\pi c)^3}\int_0^{\omega_{max}} \omega^3 d\omega \tag{15}$$

where ω_{max} is the highest frequency for which phonon modes satisfy the coherence criterion:

$$\omega_{max} = \frac{|\ \langle|\ H\ |\rangle\ |^2}{\hbar^2\omega_n} \tag{16a}$$

$$\gamma_f = \frac{3V}{8\pi^4 c^3}\frac{\omega_{max}^5}{\omega_n} \tag{16b}$$

The total fusion rate may be written in terms of the cutoff frequency in this crude model.

According to this model, the fusion rate is dominated by the highest frequency phonon modes which satisfy the coherence criterion. Moreover, an estimate of the frequency dependence of the phonon power generation spectrum is obtained. An estimate of what cutoff frequency would be required to generate a given power from a coherently fusing system can be made.

Denoting the power by $P = \gamma_f \hbar\omega_n$,

$$P = \frac{3\hbar V\omega_{max}^5}{8\pi^4 c^3} \tag{17}$$

ω_{max} is obtained.

$$\omega_{max} = [\frac{8\pi^4 c^3 P}{3V\hbar}]^{1/5} \tag{18}$$

An estimate of the maximum phonon frequency for a system with the following parameters

$$P = 1 \text{ watt}$$
$$V = 1\ cm^3$$
$$c = 3 \times 10^5 \text{ cm/sec}$$

is about 1.5 x 10^9 Hz. The interaction matrix element must have a magnitude of about 6 eV under these conditions. In terms of the interaction matrix element, the generated power is

$$P = \frac{3V \mid \langle \mid H \mid \rangle \mid^{10}}{8\pi^4 c^3 \hbar^9 \omega n^5} \tag{19}$$

which shows explicitly the strong dependence of power generation on the interaction matrix element, assuming a constant interaction matrix element.

The interaction matrix element need only be constant over a small range for the total power estimate to remain valid.

The interaction matrix element required for computation of transition rates is given by equation 20.

$$\langle \mid H \mid \rangle = \langle \Phi_0(\Gamma) \mid H_I \mid \Phi_1(\Gamma') \rangle \tag{20}$$

where Γ and Γ' denote eigenstates which differ by one acoustical phonon mode. It is assumed that nuclear fusion energy couples predominantly into acoustical phonon modes because the interaction energy required to meet the criterion set forth in Equation 8 is several orders of magnitude lower for acoustical than for optical phonons. However, optical phonon modes may be involved in this energy coupling since optical phonons are associated with relative nuclear motion which enhances tunneling probabilities moreso than lattice motion associated with acoustical phonon modes.

The dominant coupling between the nuclear fusion energy and lattice will proceed through the electromagnetic monopole E0 interaction which is stronger than an electromagnetic dipole E2 interaction because it can extend over a long range and involves an overlap integral rather than a quadrupole matrix element.

The E0 term is found to be

$$\frac{e^2}{r_>} \rightarrow \frac{2e^2}{\pi} I_0(\omega, r_i, r_j) = \frac{e^2}{\pi} \frac{1}{\omega r_i r_j} \{ ln \frac{r_j + r_i}{r_j - r_i} + g[\omega(r_j + r_i)] - g[\omega(r_j - r_i)] \} \quad (21)$$

where

$$g(z) = -Ci(z)cosz - si(z)sin2 \quad (22)$$

This more sophisticated version of the E0 operator behaves like $e^2/r_>$ over distances small compared to the wavelength of an exchanged photon, and goes as $2e^2/\omega\pi r_>^2$ in the limit that $r_>$ is much greater than the wavelength.

The wavelength of an exchanged photon can easily be on the order of the rod size or larger for coupling to acoustical phonons. Conversely, the interaction region is smaller in the case of coupling to optical phonons, since the photon wavelength becomes significantly smaller than the rod dimensions.

An order of magnitude estimate for the interaction matrix element may be obtained using equation 23.

$$\langle 0, m_K \mid H \mid 1, m_K + 1 \rangle \approx 4 I_H \frac{a_0^2}{R^2} N_C N_{pd} \sqrt{\frac{m_e}{M}} \sqrt{\frac{I_H E_K}{(\hbar\omega_K)^2 N_L}} \langle \phi_{pd} \mid \phi\ ^3He \rangle \quad (23)$$

where a_0 is the Bohr radius, I_H is 13.6eV, N_C is the number of excess charges at a mean distance R, N_L is the number of nucleons in the lattice, N_{pd} is the number of proton/deuteron pairs which are S-wave with respect to each other and where E_K is the energy in phonon mode K.

A system can be designed to optimize this interaction matrix element and obtain results which correlate with physical observables. For a centimeter scale system, with macroscopic energy applied to the lowest frequency mode in the presence of a very strong electric field, an interaction matrix element on the order of $10^{-7}eV$ can be obtained for the reaction given by Equation 1. This interaction matrix element can be substantially larger for a meter scale system, and may give rise to a measurable effect.

According to the foregoing analysis for exothermic p-d and d-d reactions (Equations 1 and 2), a reaction given by Equation 1 should only yield measurable effects for a meter scale system and is too weak to play a major role in the small scale laboratory systems characterized to date.

The model developed so far may be extended to describe the reaction of Equation 5. The larger tunneling probability of the two proton system, due to its smaller reduced mass by comparison with p-d or d-d systems, makes coherent fusion effects observable in centimeter-scale systems.

The fusion reaction product of proton-proton fusion is not a stable particle. Proton-proton fusion reactions are endothermic, and absorb rather than radiate phonons. In a coherent fusion model, two-proton fusion is predicted to occur, although not in the same way that conventional fusion occurs. The fusion reaction products would be present virtually, and would be undetectable in the absence of any additional reaction pathways. A beta decay mode is hypothesized for the virtual two-proton fusion reaction product. Also hypothesized is an ultimate product, deuterium, for the proposed two-step fusion/beta path, $d + e^+ + \nu_e$.

The reaction rate for this channel can be estimated as the product of the virtual $(^2He)_V$ probability and the associated beta decay rate. If the coupled lattice/nuclear system satisfies a coherence criterion for a low energy acoustical phonon mode, that mode will drive virtual $(^2He)_V$ production at a finite and calculable rate. As the virtual fusion products build up within the lattice, beta decay takes place more frequently. An equilibrium is established when the total rate of virtual helium creation through coherent interactions with the lattice becomes equal to the rate at which it is destroyed by beta decay. As a result, in equilibrium, we may estimate the two-step fusion/beta reaction rate from the virtual fusion rate alone using the model already developed.

These results were derived for exothermic proton-deuteron and deuteron-deuteron reactions. In the case of endothermic virtual proton-proton fusion, phonons are destroyed rather than created; nonetheless, the coherent model applies. These rates describe the production of virtual fusion product state, and some exothermic incoherent channel is required to obtain real, i.e., irreversible, reaction products in the presence of relatively constant lattice conditions.

The interaction matrix element for proton-proton reactions, H_K, may be evaluated from equation 24

$$H_K = \int E_V(r) \cdot m_K(r) d^3r \tag{24}$$

where $E_V(r)$ is the virtual electric field, and $m_K(r)$ is the monopole density.

For a system of H_2 of density n^0_{pp} placed between two very long cylindrical ca-

pacitor plates of langth L ar radii r_1 and r_2, assume that when fully charged, the capacitor develops a uniform surface charge σ_0 on the interior of the outer cylinder and a matching surface charge $-R_2\sigma_0/R_1$ on the surface of the inner cylinder.

Under these conditions, the cirtual electric field is

$$E_V(r) = \hat{i}_r 2\pi e n^0_{pp} P_0(r - \frac{R_1}{r}) \tag{25}$$

The monopole density is

$$m_K(r) = \sigma_0 \delta(r - R_2) u_K(r) \langle m_K \mid q_K \mid m_k + 1 \rangle \tag{26}$$

With these definitions, the interaction matrix element of Equation 27 can be evaluated

$$H_K = 8\pi^2 e n^0_{pp} P_0 (R_2^2 - R_1^2) L \sigma_0 u_r(R_2) \langle m_k \mid q_K \mid m_K + 1 \rangle \tag{27}$$

where $\epsilon = 1$. By symmetry, coupling occurs only with cylindrical $\hat{i}_r$-polarized modes, and of these modes only the longitudinal modes survive the spatial integration defining the continuum version of the interaction matrix element.

Assume that the total number of H_2 molecules, $N_{pp} = (R_2^2 - R_1^2) L n^0_{pp}$ is 10^{25}, and that all H_2 molecules are in the ground state, i.e., there is no vibrational or rotational excitation, then $P_0 \simeq 4x10^{-32}$ is computed numerically. For a surface charge density of 10^{11} charges/cm^2, corresponding to an applied electric field strength of 1.8 and 10^5 Volts/cm, and outer cylinder vibrating strongly in radial compressional modes of surface amplitude 0.1 cm, an interaction matrix element on the order of 0.014eV is obtained.

This example demonstrates that the interaction matrix element can be substantial under laboratory conditions. The beta decay rate, γ_β, can be estimated through the Gamow-Teller interaction for $(^2He)_V$ as $\gamma_\beta = 4x10^{-3} sec^{-1}$. In equilibrium, the total number of virtual localized proton-proton pairs can be inferred according to Equation 28

$$N_{(^2He)V} = \frac{\gamma_f}{\gamma_\beta} \tag{28}$$

It follows that some time will be required for the population of virtual pairs to build up to the equilibrium value. This time would be of the order of the beta decay time were the system linear. If the mode amplitudes themselves build up through

some other mechanism, i.e. through p+d coherent fusion, then this build-up time will be longer.

The mechanism described here also applies to the two step reaction $p + d \leftrightarrow {}^3He \rightarrow t + e^+ + \nu_e$. The coherent fusion reaction, $p + d \leftrightarrow {}^3He$, has been discussed previously, and ${}^3He$, will be present in virtual states during the course of sustained coherent fusion reactions. The interaction matrix element for the fusion process will be smaller than for two-proton coherent fusion by the ratio of tunneling factors on a per pair basis; this ratio is on the order of 10^{-4} for HD versus H_2.

A related two-step reaction which can produce neutrons is the $d + d \leftrightarrow {}^4He \rightarrow {}^3He + n$ reaction. Coherent fusion of deutrons would lead to virtual ${}^4He$, which would have a fast allowed neutron-producing decay channel.

A model for coherent fusion in which the nuclear energy is released into the acoustical phonon modes of a lattice has been developed. Coupling of the nuclear energy to the phonons can occur rapidly if the interaction couples energy one phonon at a time and if the interaction matrix element exceeds the geometric mean of the phonon energy and nuclear energy as given by Equation 3. It is important to note that this analysis applies to any type of quantized modes, mechanical, electrical, magnetic or composite as long as the coupling is strong enough to satisfy the coherence criterion of Equation 8. The coherent reactions given by Equations 1-3 can proceed through electromagnetic E0 coupling of the nucleons to excess charge in the lattice as governed by the interaction matrix element which can be calculated as previously outlined.

The fusion apparatus of this invention will now be discussed with reference to the drawing.

In Fig. 1, fusion apparatus 10 consists of containment vessel 12 for fusible material, connected electrically in series to oscillator 14 for coupling to plasmon modes and to computer-controlled variable load 16 for extracting usable energy generated by the coherent fusion process.

Vessel 12, constructed of electrically conductive material, is fabricated in a cylindrical, radially symmetric geometry and is provided with external, radially disposed, rod-like projections 18 for coupling to fusible material 20. Material 20 may include both hydrogen and deuterium with an H_2 concentration of 10^{29} atoms. In a preferred embodiment, this mixture is adjusted at a ratio 10^8 deuterons/protons to obtain p-p coupling and avoid more likely p-d coupling. Material 20 can be in the gas, liquid, or solid phase or can be maintained at a cryogenic temperature to reduce proton-

deuteron exchange. Solid material 20 can include ice or a metal hydride. Material 20 can be replenished by introduction of protons into vessel 12 from a proton source not shown. A selectively permeable membrane not shown consists of gold-coated palladium and adjusts the hydrogen-deuterium mixture. Vessel 20 may be provided with a circulation loop not shown for removal of by-products of the coherent fusion process such as tritium which accumulate during operation of apparatus 10.

Rod-like projections 18 which may be positioned on isopotential curves are electrically connected in series to oscillator 14, which can include a variable quality factor (Q) resonator not shown. Tuning such a resonator such that a low Q is selected makes the circuit "lossy" and the oscillator then functions as if it were a load, acting eventually to shut off apparatus 10. Projections 18 should be approximately one meter long for an approximately 20 meter long reactor.

One or more projections 18 can be individually coupled to high quality factor (Q) resonators, since coupling between modes is independent. In general, fusion initiation is easier for larger reactors where larger modes, having greater gain may be established.

Usable energy is extracted from fusion apparatus 10 using a computer-controlled variable load 16 which may include a switch to open electrical circuit 22, thus stopping the coherent fusion process. Load 16 may be connected to apparatus 10 in series as shown in Fig. 1a, in parallel as shown in Fig. 1b, or in parallel with variable resistor 17 as shown in Fig. 1c.

Figs. 2a and 2b show fusion apparatus 30 wherein fusible material 32 is contained within insulating containment vessel 34 and and insulating crystals 36 are disposed radially in close proximity external to vessel 34 and fusible material 32. A microwave generator not shown can be used to polarize the insulating crystals 36 and establish coupling between fusible material 32 and plasmon modes according to a method well-known to one skilled in the art. Metal positron trap 38 surrounds material 32 and crystals 36 (Fig. 2b). Heat is generated as positrons become trapped. Metals are suitable positron traps. Heat generated within the interior of apparatus 30 may be removed by thermally conductive mesh not shown embedded within vessel 34.

Fig. 3 shows an apparatus for monitoring the reaction rate of a fusion reaction. Neutron detector 40 whose fabrication is well known in the art is positioned in close proximity to coherent fusion apparatus 42. Arrow 44 represents the flux of neturons emitted as a result of the fusion process occurring within the reactor.

Neutron detector 40 can be replaced by an α-particle detector not shown whose fabrication is also well-known in the art. Since enhanced α-decay results from coherent fusion induced nuclear polarization, α-particle emission is a sensitive indicator of the coherent fusion rate.

The potential differences created by positron and annihilation γ-rays can be used to excite gas discharge laser 50 shown in Fig. 4. Current source 52 assists in fusion initiation in fusion apparatus 54 connected in parallel to current source 52 and to variable resistance element 56. Fusion apparatus 54 is also connected in parallel with electrodes 58 which are enclosed within chamber 60. Chamber 60 contains gas lasing medium 62 and a laser cavity is established in vessel 60 by installation of mirrors 63. Ground 64 is provided for laser 50 and arrow 66 indicates the direction of current flow in the circuit.

Energetic electron positron generation from a coherent fusion reactor can be electrically coupled to semiconductor laser 70 shown in Fig. 5. Current source 72 is used to assist in coherent fusion initiation in fusion apparatuses 74. Apparatuses 74 are electrically coupled to semiconductor 76. Coupling between the coherent fusion reactors and semiconductor 76 can promote a large concentration of electrons to the conduction band of the semiconductor, while a large concentration of holes are simultaneously created in the valence band. This way, the condition of population inversion required for laser operation is established.

A laser cavity is created with mirrors 78. A suitable material for semiconductor 76 should have a direct band gap and gallium arsenide, or one of its related III-V compound alloys such as $Al_xGa_{1-x}As_ySb_{1-y}$ and $Ga_zIn_{1-x}As_yP_{1-y}$. The alloy composition selected for semiconductor 76 can be chosen on the basis of the lasing wavelength required. Ground 80 is provided for laser 70 circuit and the direction of current flow is indicated by arrow 82.

The energy of the coherent fusion process can also be used to drive a vibrational laser or maser. One embodiment for a coherent fusion driven laser or maser 90 is shown in Fig. 6. Coherent fusion reactor 92 is coupled directly to laser gas 96. Energetic positron and annihilation γ-radiation can drive n=2 or higher states in virtually any molecule including CO_2, N_2, HF, CO, and O_2. The only molecules excluded are H_2, D_2 *and* HD. An optical cavity is configured using mirrors 98. Any cavity configuration can generate efficient lasing in the 0.01-0.1eV range. Efficient microwave amplifiers can also be constructed.

Energetic positrons produced by a coherent fusion reaction can also be utilized to promote chemical reactions, for example, nitrate synthesis. Nitrogen containing compounds such as NO *and* ND_3 can be produced. ND_3 can be converted to NH_3 by isotopic exchange.

Reaction vessel 100 appropriate for such a synthesis is shown in Fig. 7a. Within container 102 electrodes 104 composed of a fusion host material are immersed in a liquid medium 106 such as D_2O. Inlet 108 in container 102 permits introduction of a reactant gas such as nitrogen, N_2. The direction of gas flow is indicated by arrow 110. The coherent fusion reaction is excited by an external excitation apparatus such as a battery now shown. An insulating vessel cover 114 and electrical ground 116 are provided.

Energetic positrons promote chemical reactions near the coherent fusion reactor surface. Thus, as shown in Fig. 7b, fusion apparatus 120 is positioned in close proximity to reactants 122 which can be liquid or gas. Most reactions are expected to occur at reactor surface 124 which may be a selectively permeable gold-coated palladium membrane. Using such a configuration, a desired compound may be synthesized directly without production of a deuterated intermediate product.

It is also possible to utilize energy from a coherent fusion reaction for transmutation of elements and production of isotopes not found in nature. An apparatus for transmutation and isotope production 130 is shown in Fig. 8a. Electrodes 132 composed of a fusion host material are immersed in medium 134 containing the element to undergo transmutation in container 136. The coherent fusion reaction is initiated by an external battery, not shown. Insulating cover 138 and ground 140 are provided. Using this appartus, high atomic number radioactive isotopes may be reduced to stable isotopes through enhanced α-decay.

Transmutation of elements can be achieved by coupling fusion apparatus 150 directly to material to be transmuted 152 such as high atomic number radioactive isotopes. Selectively permeable membrane 154 which can be gold-coated palladium separates apparatus 150 from material 152.

The neutrons produced as a result of the reaction given by equation 2 can be used in neutron spectroscopy. Fig. 9 shows a coherent fusion reactor driven neutron spectrometer 160. Coherent fusion reactor 162 produces neutrons which are transferred from reactor 162 through conduit 164. Neutrons are monitored with a first monitor counter 166 and intensity may be controlled using auxiliary gate 168. A

particular neutron energy bandwidth is selected using monochromator crystal 170. Monochromatic neutrons emitted from crystal 170 are measured with second monitor counter 172 before interacting with specimen 174. Neutrons which have interacted with specimen 174 are analyzed by analyzer crystal 176 and $^{10}BF_3$ counter 178. Crystal indexing unit 180 is used for orientation of specimen 174. Spectrometer 160 is thoroughly shielded with rotatable shielding 182 and additional yoke and shielding 184 to contain stray neutron radiation.

As shown in Fig. 10, a lattice 190 including fusible material which can be a mixture of hydrogen and deuterium is bombarded by an ion beam from generator 192 to initiate coherent fusion. Energy output is represented by arrow 194.

Fig. 12 shows an amplifier 200 which consists of fusion apparatus 202 and metal plate 204 contained within a vacuum. Energetic positrons collect on surface 206 which can be a selectively permeable gold-coated palladium membrane thus establishing a potential difference of approximately MeV between surface 206 and metal plate 204 which may be positioned from surface 206. Energy may be obtained directly when positrons cross evacuated gap 208.

The reaction given by Equation 1 results in the production of ^3He, a material useful for low temperature cryogenic studies. Fig. 11 illustrates one embodiment of an apparatus for collection of ^3He collection system 210, ^3He 212 produced by coherent fusion reactor 216 is collected in gas impermeable vessel 218.

Abstract

We propose that energy from nuclear fusion reactions can be coupled to a macroscopic system coherently (in the laser sense) through electromagnetic interaction of low energy photons. We report progress on the formulation of a theory for two-step reactions in which virtual fusion is followed by exothermic incoherent decay. A new type of reaction in which incoherent electron capture is followed by coherent fusion is described.

I. Introduction

The claim of Pons and Fleischmann of the observation of fusion in an electrolysis cell[1] has been met with extreme skepticism by the scientific community[2]. The experiment has been exceptionally difficult to reproduce,[3-7] and no credible theoretical explanation of any low temperature fusion mechanism which can account for the claimed observations has been given to date.

Based on the reports of fusion at room temperature, we have been seeking new mechanisms in which fusion is enhanced in the presence of a lattice. We have proposed a coherent fusion model for p + d $\longrightarrow$ ^{3}He fusion, with the nuclear energy being radiated into the lattice phonon field, one phonon at a time through electromagnetic interaction with the lattice.[8]

In this work we report progress on the formulation of a model with which we may analyze the reaction dynamics of a class of coherent fusion reactions.

The basic premise of the theory is that off-resonant coupling between two fusing nucleons and a macroscopic system can occur through the electromagnetic interaction. An example of such a virtual fusion reaction is

$$^aH + ^bH \longleftrightarrow ^{a+b}He \qquad (I.1)$$

For example, a proton and a deuteron can fuse conventionally to ^3He following the emission of a 5.5 MeV gamma. If instead a low energy photon is exchanged, ^3He is still created, but only in a virtual sense. Our discussion applies to reactions involving other isotopes as well, but due to the low reduced mass and low Z of the hydrogen isotopes, we anticipate that non-hydrogenic reactions involving charged nucleons will be weaker.

In the absence of any further reaction pathways, the virtual fusion products are essentially nonobservable and hence of little interest. But exothermic incoherent reaction pathways exist for most of the virtual fusion products. The two-step reactions which proceed through virtual intermediate states and are of interest here include

$$p + p \longleftrightarrow (^2He)_V \longrightarrow d + e^+ + \nu_e \qquad (I.2)$$

$$p + d \longleftrightarrow (^3He)_V \longrightarrow t + e^+ + \nu_e \qquad (I.3)$$

$$d + d \longleftrightarrow (^4He)_V \begin{array}{l} \longrightarrow {}^3He + n \\ \longrightarrow t + p \end{array} \qquad (I.4)$$

$$d + t \longleftrightarrow (^5He)_V \longrightarrow {}^4He + n \qquad (I.5)$$

$$t + t \longleftrightarrow (^6He)_V \longrightarrow {}^4He + 2n \qquad (I.6)$$

In these reactions, the notation $(^nHe)_V$ denotes a virtual intermediate state. In the case of ^3He and ^4He ground state spatial orbitals, the time dependence will correspond to a state with an energy equal to the initial state energy minus the energy of the exchanged photon. These virtual fusion reactions are exothemic; additionally $d + d \longleftrightarrow {}^4He^*$ would be an exothermic virtual reaction. The other intermediate states in this scenario are localized continuum states with maximum overlap with the decay products. These virtual reactions are endothermic. A schematic of the proton-deuteron reaction is shown in Figure 1.

The incoherent branches can be either fast decays if mediated by the strong force or electromagnetic force, or else slow decays if mediated by the weak force. In the case of fast decay channels, only a small fractional virtual population needs to be established to obtain an observable decay rate. For the beta decay paths, a very large virtual population is required to produce an observable effect. The formulation which we are developing applies to both classes of reactions.

The overall scenario which we have considered works as follows: a mixture of protons and deuterons are introduced into a lattice, react virtually, and decay . The proton-proton path in this scenario produces heat, and the proton-deuterium path produces tritium. Since the beta decay is slow, a substantial virtual helium population is rquired to obtain observable levels of heat or tritium. The build-up of the virtual helium population would take time to occur. We estimate the $(^2He)_V$ decay into deuterium to take about 200 sec (from ft-theory, of Ref. 9 and 10) and therefore we require virtual $(^2He)_V$ levels to be in the vicinity of 10^{16} for a several-watt system for this scenario.

In this work we have begun as analysis of this approach. A rather immediate result of the analysis is that while the coherent fusion effects are undoubtedly real, they are clearly very small under normal conditions. The tunneling into the nuclear states is

so weak that even collective interactions have difficulty producing a net observable effect.

The original scenario seemed to be qualitatively consistent with the experimental report of Pons and Fleischmann when we began our study. We have recently learned that the measured gamma spectrum is inconsistent with positron production at levels which accompany such a picture (K. Wolf, Texas A& M, private communication). As a result, we have begun to consider the extension of the coherent model to other types of reactions. For example, the beta decay involving positron emission could be replaced with electron capture by the virtual fusion product. For example,

$$p + d + e \longleftrightarrow ({}^3He + e)_V \longrightarrow t + \nu_e \qquad (I.7)$$

Alternatively, the electron capture could occur first (leading to a virtual intermediate), and the fusion reaction would follow. For example,

$$p + d + e \longrightarrow (n + d + \nu_e)_V \longleftrightarrow t + \nu_e \qquad (I.8)$$

This type of reaction has the advantage that there is no coulomb barrier to inhibit tunneling between the fusing nucleons. Further discussion of alternate reactions of this type is given in the last section.

Our paper is organized as follows: In section II we consider nuclear populations and polarization in the presence of a semiclassical interaction hamiltonian. The model is found to be very close to semiclassical models used in laser physics. In section III we diagonalize the semiclassical hamiltonian, using a transformation which will help in analyzing more complicated systems. We next consider a quantum phonon model coupled to a classical source, and find a criterion for net phonon gain. In section V, we consider a coupled lattice nuclear system (section VI), and find that the system is approximately diagonalized with our rotation of section III. We next investigate a driven system, and find that in the dressed state picture external pertubations can create fusions through a second order interaction. In section VII we extend our analysis to include nonlinearities and strong driving terms.

II. Semiclassical Field Model

We first consider a system of pairs of hydrogen isotopes interacting with a semiclassical potential. The hamiltonian for the system is taken to be

$$\widehat{H} = \widehat{H}_N + \widehat{H}_I \qquad (II.1)$$

We will adopt a second quantization formulation (see Appendix A) for the nuclear transitions, and take $\widehat{H}_N$ to be

$$\widehat{H}_N = \frac{1}{2}\hbar\omega_n \sum_{kl} b^\dagger_{kl} b_{kl} - b_{kl} b^\dagger_{kl} \qquad (II.2)$$

where the creation and annihilation operators $b^\dagger$ and b are fermionic, and satisfy anticommutation relations

$$b^\dagger_{kl} b_{kl} + b_{kl} b^\dagger_{kl} = 1 \qquad (II.3)$$

The summation is over nucleon pairs with indicies k and l. The interaction matrix element can be written in the form

$$\widehat{H}_I = \frac{\partial H_I}{\partial b} \sum_{kl} b^+_{kl} + b_{kl} \qquad (II.4)$$

In the case of M1 interaction, $\widehat{H}_I = \hat{\mu} \cdot \hat{\mathbf{B}}$ where the magnetic dipole operator $\hat{\mu}$ is

$$\hat{\mu} = \mu \sum_{kl} b^\dagger_{kl} + b_{kl} \qquad (II.5)$$

where the single-pair magnetic dipole moment is

$$\mu = \frac{e\hbar}{2Mc} < \phi_u \mid \sum_i g^l_i \mathbf{l}_i + g^s_i \mathbf{s}_i \mid \phi_f > \qquad (II.6)$$

and where the subscripts u and f denote unfused and fused states.

We assume for simplicity that $\frac{\partial H_I}{\partial b}$ is independent of space in the vicinity of the fusing nucleons, although it can be time-dependent. The algebra for this hamiltonian is simplified if the hamiltonian is cast in terms of many-particle operators. We define three many-particle operators to be

$$\hat{\Sigma}_x = \sum_{kl} b^\dagger_{kl} + b_{kl} \qquad (II.7)$$

$$\hat{\Sigma}_y = \frac{1}{i} \sum_{kl} b^\dagger_{kl} - b_{kl} \qquad (II.8)$$

$$\hat{\Sigma}_z = \sum_{kl} b^\dagger_{kl} b_{kl} - b_{kl} b^\dagger_{kl} \qquad (II.9)$$

These operators obey commutation relations similar to many-particle spin operators. In terms of these operators, the hamiltonian is

$$\widehat{H} = \frac{1}{2}\hbar\omega_n \hat{\Sigma}_z + \frac{\partial H_I}{\partial b}\hat{\Sigma}_x \qquad (II.10)$$

The time-evolution equations for the expectation values of these operators can be found through

$$\frac{d}{dt} < \hat{\Sigma}_i >= \frac{1}{i\hbar} < [\hat{\Sigma}_i, \widehat{H}] > \qquad (II.11)$$

The resulting evolution equations are

$$\frac{d}{dt} < \hat{\Sigma}_x >= -\omega_n < \hat{\Sigma}_y > \qquad (II.12)$$

$$\frac{d}{dt} < \hat{\Sigma}_y >= \omega_n < \hat{\Sigma}_x > -\frac{2}{\hbar}\frac{\partial H_I}{\partial b} < \hat{\Sigma}_z > \qquad (II.13)$$

$$\frac{d}{dt} < \hat{\Sigma}_z >= \frac{2}{\hbar}\frac{\partial H_I}{\partial b} < \hat{\Sigma}_y > \qquad (II.14)$$

We shall define the population inversion and polarization averages to be

$$N^- =< \hat{\Sigma}_z > \qquad (II.15)$$

$$M =< \hat{\Sigma}_y > \qquad (II.16)$$

$$O =< \hat{\Sigma}_x > \qquad (II.17)$$

Our definition for the population inversion N^- follows the definition from laser physics, and is gven by the number of upper state "systems" minus lower state "systems". For example, the $p + d \longleftrightarrow (^3He)_V$ reaction is exothermic. The population inversion is given by the number of pd pairs minus the number of $(^3He)_V$ nucleii. In the case of $p + p \longleftrightarrow (^2He)_V$, which is endothermic, N^- is the population of $(^2He)_V$ minus the number of pp pairs. The energy $\hbar\omega_n$ is the positive energy difference between the upper and lower states.

Following the development which is often used in laser physics, we add relaxation terms accounting for the destruction of inversion and polarization.

$$\frac{d}{dt}N^* + \frac{N^* - N_0^*}{T_1} = \frac{2}{\hbar}\frac{\partial H_I}{\partial b}M \qquad (II.18)$$

$$\frac{d}{dt}M + \frac{M}{T_2} = \omega_n O - \frac{2}{\hbar}\frac{\partial H_I}{\partial b}N^* \qquad (II.19)$$

$$\frac{d}{dt}O + \frac{O}{T_2} = -\omega_n M \qquad (II.20)$$

A rate equation for N^* can be obtained under the assumption N^* varies slowly compared to the dynamics of M and O, and that

$$\frac{\partial H_I}{\partial b} = Re(\frac{\partial H_I}{\partial b})_0 e^{-i\omega t} \qquad (II.21)$$

Upon eliminating M and O, we obtain

$$\frac{d}{dt}N^* + \frac{N^* - N_0^*}{T_1} = -\gamma_I N^* \qquad (II.22)$$

where

$$\gamma_I = 2 \mid \frac{1}{\hbar}(\frac{\partial H_I}{\partial b})_0 \mid^2 \frac{[\omega_n^2 + \omega^2 + \frac{1}{T_2^2}]\frac{1}{T_2}}{[\omega_n^2 - \omega^2 + \frac{1}{T_2^2}]^2 + \frac{4\omega^2}{T_2^2}} \qquad (II.23)$$

In the limit that the field varies on a timescale slow compared to the nuclear oscillation time $1/\omega_n$, this becomes

$$\gamma_I = \frac{2}{T_2} \mid \frac{1}{\hbar\omega_n}(\frac{\partial H_I}{\partial b})_0 \mid^2 \qquad (II.24)$$

In the limit that $\frac{\partial H_I}{\partial b}$ oscillates on resonance with the nuclear polarization ($\omega^2 = \omega_n^2 + \frac{1}{T_2^2}$), then

$$\gamma_I = \mid \frac{1}{\hbar}(\frac{\partial H_I}{\partial b})_0 \mid^2 T_2 \qquad (II.25)$$

These limits are significant in terms of constructing a coherent fusion scenario. The two fusion states constitute a two-level system with gain or loss initially, depending on whether the virtual reaction is exothermic or endothermic. The line width is determined by T_2 for the specific reaction. In the case of strong-force mediated

decays, T_2 will be very small and the resonance will be quite broad, whereas for the reactions dominated by beta decay the lines will be very narrow.

The rate of formation of real decay products for a specific channel can be found through

$$\Gamma_i = \gamma_i \left| N^* - N_0^* \right| \qquad (II.26)$$

where γ_i is the decay rate for the upper state fusion product. The time constant T_1 is related to the incoherent decay rates through

$$\frac{1}{T_1} = \sum_i \gamma_i \qquad (II.27)$$

III. Semiclassical Hamiltonian Diagonalization

The form of the semiclassical hamiltonian

$$\widehat{H} = \frac{1}{2}\hbar\omega_n \hat{\Sigma}_z + \frac{\partial H_I}{\partial b}\hat{\Sigma}_x \qquad (III.1)$$

suggests that diagonalization can be performed through a rotation to yield

$$\widehat{H} = \frac{1}{2}\hbar\omega_n' \hat{\Sigma}_z' \qquad (III.2)$$

where the frequency of the rotated system is

$$\omega_n' = \sqrt{\omega_n^2 + (\frac{2}{\hbar}\frac{\partial H_I}{\partial b})^2} \qquad (III.3)$$

The eigenvalues of the hamiltonian are

$$E_m = \frac{1}{2}\hbar\omega_n' m \qquad (III.4)$$

where $m = -N_{kl}, \cdots, N_{kl}$.

The rotation is accomplished through the use of a unitary transformation

$$\widehat{H}' = e^{i\hat{R}}\widehat{H}e^{-i\hat{R}} \qquad (III.5)$$

where the operator $\hat{R}$ is linear in $\hat{\Sigma}_y$

$$\hat{R} = \frac{1}{2}\ tan^{-1}\left[\frac{2}{\hbar\omega_n}\frac{\partial H_I}{\partial b}\right]\hat{\Sigma}_y \qquad (III.6)$$

The picture which follows of the coupled lattice-nuclear system in this scenario is that the system possesses dressed states in which the fusion number is mixed with quantum numbers of the macroscopic system. To lowest order, a system which has an undressed fusion number equal to zero will evolve to the ground state of the dressed system with dressed fusion number equal also to zero. Due to the mixing, this dressed ground state will decay with a rate

$$\begin{aligned} \Gamma &= \sum_i \Gamma_i = \gamma_I \left| N^* \right| \\ &= \frac{2}{T_2} \left| \frac{1}{\hbar \omega_n} \left(\frac{\partial H_I}{\partial b} \right)_0 \right|^2 N_{kl} \end{aligned} \qquad (III.7)$$

assuming that $\frac{\partial H_I}{\partial b}$ is at low frequency. This decay rate is small (Typical decay rates of the order of $10^{-50} - 10^{-100}$ sec^{-1} for charged nucleons). In order to obtain observable decay rates, transitions which change the fusion number are essential. In the following sections we shall use the dressed state picture to obtain dressed terms which raise and lower the fusion number.

IV. Lattice Dynamics

We now consider the lattice dynamics under the assumption that the nuclear polarization is semiclassical. The hamiltonian for the lattice is

$$\widehat{H} = \widehat{H}_L + \widehat{H}_I \qquad (IV.1)$$

We shall restrict ourselves to single-mode interaction in this section. In this case the lattice hamiltonian is

$$\widehat{H}_L = \hbar \omega_j a^\dagger a \qquad (IV.2)$$

where the creation and annihilation operators $a^\dagger$ and a are bosonic, and satisfy the commutation relations

$$a^\dagger a - a a^\dagger = -1 \qquad (IV.3)$$

The interaction hamiltonian is will be taken to be linear

$$\widehat{H}_I = \frac{\partial H_I}{\partial a}(a^\dagger + a) \qquad (IV.4)$$

where the derivative $\frac{\partial H_I}{\partial a}$ is discussed further below and in Appendix A.

As an example, we consider the case of an electric transition, such as a $d+d$ coherent reaction which would interact through an E2 multipole. In this case, the interaction can be derived from a consideration of the potential operator, which in the coulomb limit is

$$\hat{\Phi}(\mathbf{r}) = \sum_i \frac{Z_i e}{\mid \mathbf{r} - \hat{\mathbf{r}}_i \mid} \qquad (IV.5)$$

which is valid for distances $\mid \mathbf{r} - \hat{\mathbf{r}}_i \mid$ which are small compared to the wavelength of the exchanged photon. The more general version of $\hat{\Phi}$ valid for larger distances is discussed in the appendix. The position operator of particle i is $\hat{\mathbf{r}}_i$. For a macroscopic system with collective modes we may write

$$\hat{\mathbf{r}}_i \approx \mathbf{R}_i + \sum_j \frac{\partial \hat{\mathbf{r}}_i}{\partial a_j}(a_j^\dagger + a_j) \qquad (IV.6)$$

where $\mathbf{R}_i$ is the equilibrium position of particle i. This result is valid to first order in the collective mode amplitudes. As a result, we obtain

$$\frac{\partial \Phi}{\partial a_j} = \sum_i \left(\nabla_i \frac{Z_i e}{\mid \mathbf{r} - \mathbf{r}_i \mid} \right)_{\mathbf{R}_i} \cdot \frac{\partial \hat{\mathbf{r}}_i}{\partial a_j} \qquad (IV.7)$$

The expectation value of the linearized interaction hamiltonian is

$$\begin{aligned} \langle \frac{\partial \widehat{H}_I}{\partial a} \rangle &= \frac{\partial H_I}{\partial a} \langle a^\dagger + a \rangle \\ &= \frac{\partial H_I}{\partial a} \Omega \end{aligned} \qquad (IV.8)$$

where we have defined $\Omega = \langle a^\dagger + a \rangle$. In general $\frac{\partial H_I}{\partial a}$ will be a function of space, although we have assumed it to be uniform in the previous two sections. We will require a second quantity defined by

$$\Upsilon = < \frac{1}{i}(a^\dagger - a) > \qquad (IV.9)$$

The time evolution of these expectation values is given by

$$\frac{d\Omega}{dt} + \omega_j \Upsilon = 0 \qquad (IV.10)$$

$$\frac{d\Upsilon}{dt} - \omega_j \Omega = \frac{2}{\hbar}\left(\frac{\partial H_I}{\partial a}\right) \qquad (IV.11)$$

Similar equations arise in laser physics, and correspond to the evolution of the electric field in a resonant cavity. In our case, the oscillation frequency of the interaction hamiltonian will in general not be well-matched to the cavity frequency ω_j. In the presence of damping, these equations become

$$\frac{d\Omega}{dt} + \frac{\omega_j \Omega}{2Q} + \omega_j \Upsilon = 0 \qquad (IV.12)$$

$$\frac{d\Upsilon}{dt} + \frac{\omega_j \Upsilon}{2Q} - \omega_j \Omega = \frac{2}{\hbar}\left(\frac{\partial H_I}{\partial a}\right) \qquad (IV.13)$$

where Q is the quality factor of the mode.

A possible coherent fusion scenario which might be proposed is one in which the nuclear polarization is driven at low frquency (ω_j). The nuclear system is initially inverted in the case of exothermic reactions and, if so, there is the possibility that the low frequency mode is driven. We can analyze this scenario within the framework of our model by noting that the classical nuclear polarization is defined in terms of the nuclear polarization expectation value

$$\begin{aligned} \frac{\partial H_I}{\partial a} &= \langle \frac{\partial \widehat{H}_I}{\partial a} \rangle \\ &= \frac{\partial^2 H_I}{\partial a \partial b} \langle \Sigma_x \rangle \end{aligned} \qquad (IV.14)$$

If we assume that the interaction hamiltonian is approximately sinusoidal, then we may use the results of section II to relate the lattice polarization to the nuclear polarization. If we assume that $\frac{\partial H_I}{\partial a}(t) = R_e(\frac{\partial H_I}{\partial a})_0 e^{-i\omega t}$ with $(\frac{\partial H}{\partial a})_0$ slowly varying in time, then we obtain

$$< \Sigma_x >= \frac{2}{\hbar}\frac{\partial^2 H_I}{\partial a \partial b}\frac{\omega_n}{\omega_n^2 - (\omega + i/T_2)^2} N^* \Omega \qquad (IV.15)$$

The criterion which must be met in order for the mode to exponentiate in the linear regime is

$$\frac{4\omega N^*}{\omega_n T_2}\left[\frac{1}{\hbar\omega_n}\frac{\partial^2 H_I}{\partial a \partial b}\right]^2 > \frac{\omega_j}{2Q} \qquad (IV.16)$$

in the case of an exothermic virtual fusion reaction. This constraint appears to be quite severe, and it is not obvious that it can be met without substantial enhancements in tunneling.

V. Coupled Lattice - Nuclear Dynamics

The hamiltonian for the combined nuclear and lattice system is

$$\widehat{H} = \widehat{H}_N + \widehat{H}_L + \widehat{H}_I \qquad (V.1)$$

In terms of the operators defined in the previous sections, this can be written as

$$\widehat{H} = \frac{1}{2}\hbar\omega_n\widehat{\Sigma}_z + \frac{\partial^2 H_I}{\partial a \partial b}\widehat{\Sigma}_x(a^\dagger + a) + \hbar\omega_j a^\dagger a \qquad (V.2)$$

We may diagonalize the first two terms of the hamiltonian using a rotation similar to the transformation of section III. This leads to a transformed hamiltonian given by

$$\begin{aligned}\widehat{H'} &= e^{i\widehat{R}}\widehat{H}e^{-i\widehat{R}} \\ &= \frac{1}{2}\hbar\omega_n'\widehat{\Sigma}_z + \hbar\omega_j e^{i\widehat{R}}a^\dagger a e^{-i\widehat{R}}\end{aligned} \qquad (V.3)$$

The rotation operator in this case is

$$\widehat{R} = \frac{1}{2}\ tan^{-1}\left[\frac{2}{\hbar}\frac{\partial^2 H_I}{\partial a \partial b}(a^\dagger + a)\right]\widehat{\Sigma}_y \qquad (V.4)$$

We note that ω_n' is an operator in this formulation

$$\omega_n' = \sqrt{\omega_n^2 + (\frac{2}{\hbar})^2(\frac{\partial \widehat{H}_I}{\partial b})^2} \qquad (V.5)$$

We can compute the leading terms of (V.3) by assuming that $\widehat{R}$ is small, specifically using

$$e^{i\widehat{R}}a^\dagger a e^{-i\widehat{R}} = a^\dagger a + i\left[\widehat{R}, a^\dagger a\right] + \cdots \qquad (V.6)$$

The resulting transformed hamiltonian is

$$\widehat{H'} = \frac{1}{2}\hbar\omega_n'\widehat{\Sigma}_z + \hbar\omega_j a^\dagger a + \frac{\omega_j}{\omega_n}\frac{\partial^2 H_I}{\partial a \partial b}\widehat{\Sigma}_y\frac{(a^\dagger - a)}{i} \qquad (V.7)$$

valid to first order in $\widehat{\Sigma}_y$. The interaction term which arises is smaller than the original interaction by a factor of ω_j/ω_n. One could perform a second rotation and eliminate

this coupling term, but given the smallness of the interaction, it does not appear at this point to be necessary.

To lowest order little happens in a system initially in the unfused state ($\hat{\Sigma}_z\Psi_0 = \pm N_{kl}\Psi_0$) of the transformed system. In the dressed state picture, the coupled system remains in the initial state (which has a small component which decays according to the results of section II), and essentially no further fusion occurs. Larger total decay rates would be obtained if transitions to states of higher fusion number could be made; such transitions require additional terms in the hamiltonian, which we consider in the following sections.

VI. A Driven Coupled Nuclear-Lattice System

In the presence of an external driving term, the hamiltonian is

$$\widehat{H} = \widehat{H}_N + \widehat{H}_L + \widehat{H}_I + \widehat{H}_{ext} \qquad (VI.1)$$

As before we will recast $\widehat{H}$ in terms of the operators defined previously. This yields

$$\begin{aligned} \widehat{H} &= \frac{1}{2}\hbar\omega_n\hat{\Sigma}_z + \frac{\partial^2 H_I}{\partial a \partial b}\hat{\Sigma}_x(a^\dagger + a) + \hbar\omega_i a^\dagger a \\ &+ \left(\frac{\partial H_{ext}}{\partial a}\right)^{(1)}(a^\dagger + a) + \left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)}\frac{(a^\dagger - a)}{i} \end{aligned} \qquad (VI.2)$$

where we have kept only first order terms in the external hamiltonian. The first term of the external hamiltonian is proportional to $(a^\dagger + a)$, which is a position operator. The second term is proportional to $(a^\dagger - a)/i$ which is a velocity operator.

Using the rotation of section V leads to a transformed hamiltonian

$$\begin{aligned} \widehat{H'} &= e^{i\hat{R}}\widehat{H}e^{-i\hat{R}} \\ &= \frac{1}{2}\hbar\omega_n'\hat{\Sigma}_z + \hbar\omega_j a^\dagger a + \frac{\omega_j}{\omega_n}\frac{\partial^2 H_I}{\partial a \partial b}\hat{\Sigma}_y\frac{(a^\dagger - a)}{i} \\ &+ \left(\frac{\partial H_{ext}}{\partial a}\right)^{(1)}(a^\dagger + a) + e^{i\hat{R}}\left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)}\frac{(a^\dagger - a)}{i}e^{-i\hat{R}} \end{aligned} \qquad (VI.3)$$

In this result we have kept only the lowest order term arising from the transformation of $\widehat{H}_L$. Additionally, $(a^\dagger + a)$ commutes with $\hat{R}$, so that the first external term is unchanged after the transformation. To lowest order, we find

$$e^{i\hat{R}}\left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)}\frac{(a^\dagger - a)}{i}e^{-i\hat{R}} =$$

$$\left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)} \frac{(a^\dagger - a)}{i} + \left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)} \left[\widehat{R}, a^\dagger - a\right] \qquad (VI.4)$$

After performing the commutation we obtain the low order transformed hamiltonian

$$\begin{aligned} \widehat{H'} &= \frac{1}{2}\hbar\omega_n'\widehat{\Sigma}_z + \hbar\omega_j a^\dagger a + \frac{\omega_j}{\omega_n}\frac{\partial^2 H_I}{\partial a \partial b}\widehat{\Sigma}_y \frac{(a^\dagger - a)}{i} \\ &+ \left(\frac{\partial H_{ext}}{\partial a}\right)^{(1)}(a^\dagger + a) + \left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)} \frac{(a^\dagger - a)}{i} \\ &- \frac{2}{\hbar\omega_n}\left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)} \frac{\partial^2 H_I}{\partial a \partial b}\widehat{\Sigma}_y \end{aligned} \qquad (VI.5)$$

The new addition to our dressed-state hamiltonian is a term which combines the out-of-phase (velocity-dependent) external driving hamiltonian to a fusion polarization operator.

Some comments on this new term are in order. It is basically a second order effect relative to the initial lattice-nuclear coupling, except that it has the potential of being amplified since $\left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)}$ may be very large. The increase in observable decay rate due to the external hamiltonian is

$$\Gamma' = \frac{8N_{kl}}{T_2}\left[\frac{1}{\hbar\omega_n}\frac{\partial^2 H_I}{\partial a \partial b}\right]^2 \frac{1}{(\hbar\omega_n)^2}\left[\left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)}\right]^2 \qquad (VI.6)$$

This effect increases the decay rate, but since it is assumed to be off-resonant, it appears difficult to produce substantial observable effects without enhancements of the tunneling probability.

VII. Nonlinearities and Strong Driving Terms

The only way that large enough decay rates to produce observable effects can follow from a coherent fusion theory in the absence of strong tunneling enhancement, especially in the case of weak interaction decay reactions, is if high frequency potential oscillations are developed. Such effects are not produced by first order terms in the hamiltonian, and hence one would not expect to see any coherent fusion effects in an unstressed macroscopic system in the elastic limit. Hence we are forced to consider the possibility of adding terms which are of extreme order in a and $a^\dagger$.

Having postulated that the presence of high order nonlinearities is required to make futher progress in the theory, we face the difficulty of analyzing the system

which is proposed. We shall begin the analysis, and we have a formulation which may in the future lead to a more tractable theory, but the discussion of this section must be viewed as the beginning of a larger and possibly involved effort.

The hamiltonian which we postulate is written as

$$\widehat{H} = \frac{1}{2}\hbar\omega_n\hat{\Sigma}_z + \frac{\partial^2 H_I}{\partial a \partial b}\hat{\Sigma}_x(a^\dagger + a) + \widehat{H}_L + \widehat{H}_{ext} \qquad (VII.1)$$

where $\widehat{H}_L$ and $\widehat{H}_{ext}$ are now assumed to be highly nonlinear in a and $a^\dagger$. The dressed state hamiltonian is to lowest order

$$\widehat{H}' = \frac{1}{2}\hbar\omega_n' + \widehat{H}_L + i[\hat{R}, \widehat{H}_L] + i\left[\hat{R}, \widehat{H}_{ext}\right] \qquad (VII.2)$$

where $\hat{R}$ is given in (V.4). Let us define

$$\hat{\Xi} = i[\frac{1}{2}\tan^{-1}\left[\frac{2}{\hbar\omega_n}\frac{\partial^2 H_I}{\partial a \partial b}(a^\dagger + a)\right], \widehat{H}_L + \widehat{H}_{ext}] \qquad (VII.3)$$

The dressed state hamiltonian becomes

$$\widehat{H}' = \frac{1}{2}\hbar\omega_n'\hat{\Sigma}_z + \widehat{H}_L + \hat{\Xi}\hat{\Sigma}_y \qquad (VII.4)$$

From this form of the dressed state hamiltonian we may obtain the resonance virtual fusion decay rate to be

$$\Gamma' = \frac{N_{kl}T_2}{\hbar^2} |< \hat{\Xi}(\omega = \sqrt{\omega_n^2 + 1/T_2^2}) >|^2 \qquad (VII.5)$$

For a frequency-dependent nonlinear interaction matrix element, we may generalize this result to

$$\Gamma' = \frac{2N_{kl}}{\hbar^2}\int_0^\infty |< \Xi(\omega) >|^2 \frac{[\omega_n^2 + \omega^2 + 1/T_2^2]}{[\omega_n^2 - \omega^2 + 1/T_2^2]^2 + 4\omega^2/T_2^2}d\omega \qquad (VII.6)$$

This result is useful as a formal result for the incoherent decay of a coupled system. It is not easily amenable to further quantification in the absence of models for $\widehat{H}_L$ and $\widehat{H}_{ext}$ which are tractable.

We note that there is an alternate approach to the computation of the dressed state interaction term. In this case we discard a and $a^\dagger$ as the primary macroscopic operators, and work instead directly with the individual particle position and momentum operators. We consider the coupled lattice-nuclear hamiltonian

$$\widehat{H} = \frac{1}{2}\hbar\omega_n\hat{\Sigma}_z + \frac{\partial\widehat{H}_I}{\partial b}\hat{\Sigma}_x + \sum_i \frac{|\,\hat{\mathbf{p}}_i\,|^2}{2m_i} + \sum_{i<j} V(|\,\hat{\mathbf{r}}_i - \hat{\mathbf{r}}_j\,|) + \widehat{H}_{ext} \qquad (VII.7)$$

In this formulation, the coordinate positions $\mathbf{r}_i$ and momenta $\mathbf{p}_i$ are taken to be the primary operators.

The infinitesmal rotation operator is

$$\hat{R} = \frac{1}{2}\ tan^{-1}\left[\frac{2}{\hbar\omega_n}\frac{\partial\widehat{H}_I}{\partial b}\right]\hat{\Sigma}_y \qquad (VII.8)$$

The transformed hamiltonian becomes to lowest order in $\hat{\Sigma}_y$

$$\begin{aligned}\widehat{H}' = \frac{1}{2}\hbar\omega_n'\hat{\Sigma}_z &+ \sum_i \frac{|\,\hat{\mathbf{p}}_i\,|^2}{2m_i} + \sum_{i<j} V(|\,\hat{\mathbf{r}}_i - \hat{\mathbf{r}}_j\,|) + \widehat{H}_{ext} \\ &+ i\frac{\hat{\Sigma}_y}{\hbar\omega_n}\left[\frac{\partial\widehat{H}_I}{\partial b}, \sum_i \frac{|\,\hat{\mathbf{p}}_i\,|^2}{2m_i}\right] + i\frac{\hat{\Sigma}_y}{\hbar\omega_n}\left[\frac{\partial\widehat{H}_I}{\partial b}, \widehat{H}_{ext}\right]\end{aligned} \qquad (VII.9)$$

for the case of electric E1, E1, ... transitions involving very low energy photon exchange (since $\frac{\partial\widehat{H}_I}{\partial b}$ is only a function of coordinates $\hat{r}_i$, and not momenta $\hat{\mathbf{p}}_i$). The extension to the magnetic case is straightforward.

In terms of the coordinate-based operators, the dressed state interaction operator $\hat{\Xi}$ is

$$\hat{\Xi} = i\frac{1}{\hbar\omega_n}\left[\frac{\partial\widehat{H}_I}{\partial b}, \sum_i \frac{|\,\hat{\mathbf{p}}_i\,|^2}{2m_i}\right] + i\frac{1}{\hbar\omega_n}\left[\frac{\partial\widehat{H}_I}{\partial b}, \widehat{H}_{ext}\right] \qquad (VII.10)$$

In this formulation, a single dressed state fusion transition is coupled to a macroscopic transition operator. If the exchange involves a large amount of energy ($\hbar\omega_n$), then it is possible for the interaction to be resonant with the nuclear system. In the dressed state formulation, even though such a transition involves a great deal of energy, the net interaction is made of a large number of low energy coulombic photon exchanges with the nucleii. As a result, the effective interaction can be long range.

VIII. Summary and Conclusions

We have described progress which we have made towards the development of a coherent fusion theory. The premise of this type of theory is that a fusion reaction which can occur through the emission of a high energy gamma can also proceed, at

least in principle, through the successive emission of a large number of low energy photons. In of itself, such an observation is not immediately useful, since the multi-photon process will be of high order and hence occur only weakly. If a large number of identical fusion reactions are involved in the process, then a significant enhancement of the low energy photon emission rate may be possible if the low energy photons are emitted coherently.

There are, however, two distinct problems which must be faced in order to account for the Pons-Fleischmann effect within the framework of the coherent fusion picture. Not only must nuclear energy be coupled from the microscopic to the macroscopic coherently, but some way must be found in order to overcome the coulomb barrier. Our efforts included consideration of proton-proton fusion, since it appeared to have the largest tunneling probability of all fusion reactions between charged nucleons. Although it was obvious at the outset of the work that it would be very difficult to obtain an effect sufficiently large to be observable from such premises, we found motivation from the similarities between the reported experimental observations and the qualitative features of a coherent fusion theory. We had hoped that through our investigations that some new piece of physics would turn up which would account for an enhancement in tunneling.

In fact, after this paper had been written and submitted, it occured to us that two-step beta/fusion reactions involving an intermediate neutron might provide an answer to the tunneling problem. There was not time to develop a model for the new reaction and to write a new paper; it was decided to retain most of the initial paper and to supplement it with some discussion of the new ideas. Our hope is that these ideas can help in the development of a quantitative theory for the Pons-Fleischmann effect.

We have modeled systems in which coherent fusion is followed by incoherent decay. Our principal result in this area is simply making a connection between laser physics and the fusion problem. Additionally, we have found that the rates for coherent two-step fusion/beta reactions are very small, under a variety of assumptions. One of our goals was to attempt to exploit collective effects without altering the tunneling probabilities substantially in accounting for the Pons-Fleischmann effect. In this respect we have not succeeded in the case of fusion/beta reactions.

These conclusions prompted us to consider the coherent fusion mechanism on an alternate class of virtual reactions. For example, a related two-step proton-deuteron

reaction which we propose

$$e + p + d \longrightarrow (n + d + \nu_e)_V \longleftrightarrow t + \nu_e \qquad (VIII.1)$$

In this type of reaction, the electron capture would precede the virtual fusion reaction. It is illustrated in Figure 2. The advantage of this type of reaction is that the fusion would occur between a neutral particle and a charged particle, and hence there is the possibility of obtaining a substantial tunneling probability for the coherent fusion branch of the reaction. This reaction would be responsible for tritium production in our new scenario.

Heat production would follow from a similar beta/fusion reaction, specifically

$$e + p + p \longrightarrow (n + p + \nu_e)_V \longleftrightarrow d + \nu_e \qquad (VIII.2)$$

as shown in Figure 3.

This reaction might proceed as follows: a proton would tunnel into the outer electron orbitals of a nearby metal atom, and pick up an electron through the weak interaction electron capture process. The resulting state would be virtual, since it is not energetically allowed. The fusion of the neutron and a second proton would occur through the coherent fusion (electromagnetic M1 interaction) mechanism discussed in this paper, driven by a relatively large magnetic dipole associated with neutral system tunneling. Overall, this process is somewhat related to two-photon decay. The neutrino spectrum would be continuous, and the remaining nuclear energy would be converted to heat through interaction with the current.

The basic mechanism can in principle be extended to higher Z systems. For example, a two-step reaction involving lithium is proposed:

$$e + p + {}^6Li \longrightarrow (n + {}^6Li + \nu_e)_V \longleftrightarrow {}^7Li + \nu_e \qquad (VIII.3)$$

This reaction is of interest since it can be mediated by electromagnetic E1 interaction for s-wave neutron-lithium channels, which we believe should be dominant.

The principle can be extended to higher Z coherent fusion reactions. For example, the two-step reaction

$$e + p + {}^{104}Pd \longrightarrow (n + {}^{104}Pd + \nu_e)_V \longleftrightarrow {}^{105}Pd + \nu_e \qquad (VIII.4)$$

could occur through electromagnetic E2 interaction for s-wave channels. (This proposal is in part motivated by the recent experimental observations of O'Grady at Naval Research Laboratory.) The other stable Pd isotopes could react similarly.

We have focused on proton reactions in our examples because proton would appear to be favored due to the small reduced mass. Similar reactions initiated by electron capture of deuterium or tritium are also possible, as illustrated in Figure 4.

We provide some initial discussion of the formulation of a model for this type of reaction in Appendix B. Some work remains in the development of coherent fusion theory before it becomes quantitative (the reader may provide his/her own judgement on how much). Our focus has been on mechanism, and experiments can shed light on the correctness of our premises (Is deuterium produced consistent with heat? Are neutrinos produced at substantial rates?).

In conclusion, we have proposed and explored a new scenario and several new reactions in an attempt to account for the Pons-Fleischmann effect.

Appendix A: Second Quantization Operators

The quantities which appear in section II can be determined from the matrix element derived from the lowest order Feynman diagram for single photon exchange. This matrix element is

$$\langle \Gamma \mid H_I \mid \Gamma' \rangle =$$

$$\sum_i \sum_{kl} \langle \Gamma \mid \left[\frac{2}{\pi} \frac{f(K \mid \mathbf{r}_i - \mathbf{r}_k \mid)}{\mid \mathbf{r}_i - \mathbf{r}_k \mid} \right] \left[\rho_i \rho_k - \frac{\mathbf{j}_i \cdot \mathbf{j}_k}{c^2} \right] \mid \Gamma' \rangle$$
$$+ \sum_i \sum_{kl} \langle \Gamma \mid \left[\frac{2}{\pi} \frac{f(K \mid \mathbf{r}_i - \mathbf{r}_l \mid)}{\mid \mathbf{r}_i - \mathbf{r}_l \mid} \right] \left[\rho_i \rho_l - \frac{\mathbf{j}_i \cdot \mathbf{j}_l}{c^2} \right] \mid \Gamma' \rangle \qquad (A.1)$$

In this formula, the summation over i includes all particles in the lattice, the summation over k and l is over all pairs of hydrogen isotopes, and K is the wavevector $(2\pi/\lambda)$ of the exchanged photon. The function f is defined in terms of cosine and sine integrals.

$$f(z) = Ci(z)\sin(z) - si(z)\cos(z) \qquad (A.2)$$

In the low energy limit ($K \longrightarrow 0$) we note that

$$\lim_{K \longrightarrow 0} \frac{2}{\pi} \frac{f(K \mid \mathbf{r}_i - \mathbf{r}_k \mid)}{\mid \mathbf{r}_i - \mathbf{r}_k \mid} = \frac{1}{\mid \mathbf{r}_i - \mathbf{r}_k \mid} \qquad (A.3)$$

For relativistic electrons, $\mathbf{j}$ and ρ_i commute with $\mathbf{r}_i$; in other cases (A.1) must be symmetrized with respect to noncommuting variables.

Our goal is to build up a model in which the fusion energy is coupled from the microscopic to the macroscopic. This will be easiest to accomplish when the interaction is long range, which immediately suggests that we should concentrate on low energy photon exchange (where λ is greater than the system dimensions). For example, coupling to mechanical or acoustical modes can be done with relatively low energy photons; plasmon generation in a metal will involve photons of several electron volts and will therefore be, of shorter range.

The interactions described in (A.1) are electrical or magnetic at low energy. The longest range interaction is the monopole interaction. For example, in the low energy limit where (A.3) is appropriate, then

$$\frac{1}{\mid \mathbf{r}_i - \mathbf{r}_k \mid} = \sum_{lm} \frac{4\pi}{(2l+1)} \frac{r_<^l}{r_>^{l+1}} Y_{lm}^*(\mathbf{r}_i) Y_{lm}(\mathbf{r}_k) \qquad (A.4)$$

The monopole case is where $l = 0$, and the interaction strength is proportional to $1/r$. Unfortunately, the matrix element on the microscopic scale is normally zero for an E0 transition for well-separated particles. A microscopic electric dipole (E1) transition couples to free charge with a $1/r^2$ dependence, but it requires p-wave interaction between the nucleons at the microscopic scale for light hydrogen (p and d) isotope reactions. For two-step reactions where fusion occurs first, only the s-wave interactions have any chance of contributing at low temperature. As a result, the electric quadrupole (E2) interaction will in general do best of the electric interactions for these systems, and it varies as $1/r^3$.

The allowed magnetic interactions under the assumption of microscopic s-wave interaction to even parity final states are odd-multiple (M1, M3, ...) interactions. The magnetic dipole (M1) interaction will be the strongest, and is proportional to $1/r^2$ at low energy. The dipole occurs at the nuclear microscopic half of the total interaction, while the macroscopic part of the interaction involves macroscopic current flow. Spin-spin interaction is also possible, but varies as $1/r^3$.

The dominant long range interaction (in the absence of electric and magnetic monopole transitions) is the M1 interaction, for even parity final states for which the interaction hamiltonian at low energy is customarily taken to be

$$H_I = -\mu \cdot \mathbf{B} \tag{A.5}$$

In the case of the two-step reactions described in section VIII, the neutron need not necessarily be at low energy relative to the charged nucleus. At low energy the above arguments still hold, but at high energy p-wave terms are possible, and the coupling can in principle occur through E1 interaction.

We can simplify the matrix element through the use of the Hartree approximation. In this approximation, we separate the total macroscopic wavefunction $\mid \Gamma\rangle$ into a product of a local part $\mid \phi_\Gamma\rangle_{kl}$ which includes the two fusing hydrogen isotopes, and $\mid \overline{\Gamma}\rangle$ which includes the remaining part of $\mid \Gamma\rangle$. The electrical part of the interaction in this approximation is

$$\langle \Gamma \mid H_E \mid \Gamma' \rangle = \sum_{kl} \sum_{LM} \langle \phi_\Gamma \mid \rho_{LM} \mid \phi_{\Gamma'} \rangle_{kl} \Phi_{LM}(\mathbf{r}_{kl}) \tag{A.6}$$

where

$$\Phi_{LM}(\mathbf{r}) = \sum_i \langle \overline{\Gamma} \mid \frac{Z_i e Y_{LM}(\frac{\mathbf{r}-\mathbf{r}_i}{|\mathbf{r}-\mathbf{r}_i|})}{\mid \mathbf{r} - \mathbf{r}_i \mid^{L+1}} \mid \overline{\Gamma}' \rangle \tag{A.7}$$

and where

$$\rho_{LM} = Q^E_{LM} = \sum_i \frac{e}{2}[1+\tau_3(i)]r_i^L Y^*_{LM}(\hat{r}_i) \qquad (A.8)$$

in the low energy limit. In this formula, we have assumed in addition that the principal interaction is long range such that $\mid \mathbf{r}_i - \mathbf{r}_k \mid = \mid \mathbf{r}_i - \mathbf{r}_l \mid = \mid \mathbf{r}_i - \mathbf{r}_{kl} \mid$. The coordinate $\mathbf{r}_{kl}$ in this formula denotes the location of the fusion product.

In the limit that the wavelength of the exchanged photon is long compared to the nuclear scale, but otherwise arbitrary, then (A.4) is replaced by

$$\frac{2}{\pi}\frac{f(K \mid \mathbf{r}_i - \mathbf{r}_k \mid)}{\mid \mathbf{r}_i - \mathbf{r}_k \mid} = \sum_{lm} 8\int_0^\infty \frac{k}{K+k} j_l(kr_1) j_l(kr_2) dk Y^*_{lm}(\hat{\mathbf{r}}_1) Y_{lm}(\hat{\mathbf{r}}_2) \qquad (A.9)$$

and Φ_{LM} becomes

$$\Phi_{LM}(\mathbf{r}) =$$

$$\sum_i \langle \overline{\Gamma} \Big| Z_i e Y_{LM}\left(\frac{\mathbf{r}-\mathbf{r}_i}{\mid \mathbf{r}-\mathbf{r}_i \mid}\right) \frac{\sqrt{\pi}}{\Gamma(L+\frac{3}{2})2^{L+1}} \int_0^\infty \frac{k^{L+1}}{\omega+k} j_L(k \mid \mathbf{r}-\mathbf{r}_i \mid) dk \Big| \overline{\Gamma}' \rangle \qquad (A.10)$$

The magnetic part of the interaction becomes

$$\langle \Gamma \mid H_M \mid \Gamma' \rangle = -\frac{1}{c}\sum_{kl}\sum_{LM} \langle \phi_\Gamma \mid \mathbf{J}_{LM} \mid \phi_{\Gamma'} \rangle_{kl} \cdot \mathbf{A}_{LM}(\mathbf{r}_{kl}) \qquad (A.11)$$

where

$$\langle \phi_\Gamma \mid \mathbf{J}_{LM} \mid \phi_{\Gamma'} \rangle_{kl} = \sum_i \frac{1}{2} \langle \phi_\Gamma \Big| r_i^L Y^*_{LM} \mathbf{j}_i + \mathbf{j}_i r_i^L Y_{LM} \Big| \phi_{\Gamma'} \rangle \qquad (A.12)$$

and

$$\mathbf{A}_{LM}(\mathbf{r}) = \sum_i \langle \overline{\Gamma} \Big| \mathbf{j}_i \frac{Y_{LM}}{\mid \mathbf{r}-\mathbf{r}_i \mid^{L+1}} + \frac{Y_{LM}}{\mid \mathbf{r}-\mathbf{r}_i \mid^{L+1}} \mathbf{j}_i \Big| \Gamma \rangle \qquad (A.13)$$

The generalization to the case where the wavelength of the exchanged photon is much larger than nuclear size scales, but otherwise arbitrary, is obtained through the use of (A.9), as before.

We have defined matrix elements thus far which allow us to handle both electric and magnetic coupling for arbitrary multipolarity. We are ignoring free photon emission in the present work. At this point we shall focus on the magnetic M1 interaction, although it is clear that we are in a position to adapt our formulation to other cases.

The M1 matrix element is

$$\begin{aligned}\langle \Gamma \mid H_M \mid \Gamma' \rangle &= -\frac{1}{c}\sum_{kl}\sum_{M=-1}^{1} \langle \phi_\Gamma \mid \mathbf{J}_{1M} \mid \phi_{\Gamma'} \rangle_{kl} \cdot \mathbf{A}_{1M}(\mathbf{r}_{kl}) \\ &= -\sum_{kl} \langle \phi_\Gamma \mid \mu \mid \phi_{\Gamma'} \rangle_{kl} \cdot \mathbf{B}(\mathbf{r}_{kl})\end{aligned} \tag{A.17}$$

where

$$\mathbf{B}(\mathbf{r}) = \frac{1}{c}\nabla \times \sum_i \langle \overline{\Gamma} \mid \frac{1}{2}(\mathbf{j}_i \frac{1}{\mid \mathbf{r} - \mathbf{r}_i \mid} + \frac{1}{\mid \mathbf{r} - \mathbf{r}_i \mid}\mathbf{j}_i) \mid \overline{\Gamma}' \rangle \tag{A.18}$$

and the magnetic moment is

$$\mu = \sum_i g_i^{(l)} \mathbf{l}_i + g_i^{(s)} \mathbf{s}_i \tag{A.19}$$

Some simplification is afforded if the dipole moments are taken to be uniform for all pairs. For example, in HD gas at very low temperature all pairs would be in the ground state, and all molecules with identical relative $\mathbf{J}$ will possess identical moments. In this limit, we may define a spatially dependent polarization operator to be

$$0(\mathbf{r}) = \sum_{kl} \delta^3(\mathbf{r} - \mathbf{r}_{kl}) \tag{A.20}$$

In terms of these operators, the interaction matrix element becomes

$$\langle \Gamma \mid H_I \mid \Gamma' \rangle = \mu \cdot \int 0(\mathbf{r}) \langle \overline{\Gamma} \mid \mathbf{B}(\mathbf{r}) \mid \overline{\Gamma}' \rangle d^3\mathbf{r} \tag{A.21}$$

The transition to a second quantization picture can now be made. At the location $\mathbf{r}_{kl}$, the two hydrogen isotopes can either be fused or not. The interaction matrix element is of interest when a fusion transition occurs, either creation of a fused state (we shall adopt $b_{kl}^\dagger$ to describe the transition to a fused state) or destruction of a fused state (b will be the annihilation operator). The second quantized version of the polarization operator is

$$\hat{0}(\mathbf{r}) = \sum_{kl} \delta^3(\mathbf{r} - \mathbf{r}_{kl})(b_{kl}^\dagger + b_{kl}) \tag{A.22}$$

The $b_{kl}^\dagger$ operators must be fermionic, since once two hydrogen isotopes have fused, they are assumed not to be able to fuse further.

If we define spatially dependent versions of the inversion and polarization operators

$$\widehat{N}^*(\mathbf{r}) = \sum_{kl} \delta^3(\mathbf{r} - \mathbf{r}_{kl})(b_{kl}^\dagger b_{kl} - b_{kl} b_{kl}^\dagger) \tag{A.23}$$

and

$$\widehat{M}(\mathbf{r}) = \sum_{kl} \delta^3(\mathbf{r} - \mathbf{r}_{kl}) \frac{(b_{kl}^\dagger - b_{kl})}{i} \tag{A.24}$$

then we would obtain a spatially-dependent version of the equations (II.18 - II.20).

If $\mathbf{B}(\mathbf{r})$ is considered to be an operator (in terms of $\hat{\mathbf{r}}_i$), then the interaction matrix element becomes

$$\langle \Gamma \mid H_I \mid \Gamma' \rangle = \langle \Gamma \mid \mu \cdot \int \hat{0}(\mathbf{r}) \hat{\mathbf{B}}(\mathbf{r}) d^3\mathbf{r} \mid \Gamma' \rangle \tag{A.25}$$

This is ultimately the basis for the discussion of section VII.

We have chosen to work with an assumption that the interaction is uniform in the vicinity of the fusing hydrogen isotopes. This corresponds to the Dicke superradiant limit of this type of model, and allows us to exploit the rotation transformations introduced in section III. Under this assumption, (A.12) becomes

$$\langle \Gamma \mid H_I \mid \Gamma' \rangle = \langle \Gamma \mid \mu \cdot \int \hat{0}(\mathbf{r}) d^3\mathbf{r} \hat{\mathbf{B}} \mid \Gamma' \rangle \tag{A.26}$$

The integral in (A.13) is computed

$$\int \hat{0}(\mathbf{r}) d^3\mathbf{r} = \sum_{kl} (b_{kl}^\dagger + b_{kl}) \tag{A.27}$$

which is a space-independent version of $\hat{0}$ which we have used in section II. Using $\hat{\mu} = \mu \sum_{kl} (b_{kl}^\dagger + b_{kl})$, we obtain

$$\langle \Gamma \mid H_I \mid \Gamma \rangle = \langle \Gamma \mid \hat{\mu} \hat{\mathbf{B}} \mid \Gamma' \rangle \tag{A.28}$$

which is the premise of equation (II.4).

In order to free ourselves from a particular multipolarity, we will work in terms of $\widehat{H}_I$. For magnetic dipole interaction, we define

$$\begin{aligned} \widehat{H}_I &= \sum_{kl} \frac{\partial \widehat{H}_I}{\partial b_{kl}} (b_{kl}^+ + b_{kl}) \\ &\approx \frac{\partial \widehat{H}_I}{\partial b} \hat{0} = \frac{\partial \widehat{H}_I}{\partial b} \hat{\Sigma}_x \end{aligned} \tag{A.29}$$

For section IV, we have

$$\begin{aligned} \widehat{H}_I &= \sum_{ij} (\nabla_i \widehat{H}_I) \cdot \frac{\partial \mathbf{r}_i}{\partial a_j} (a_j^\dagger + a_j) \\ &= \sum_j \frac{\partial \widehat{H}_I}{\partial a_j} (a_j^\dagger + a_j) \end{aligned} \tag{A.30}$$

For section V, we extend this to

$$\begin{aligned} \widehat{H}_I &= \sum_i \sum_{kl} \frac{\partial^2 \widehat{H}_I}{\partial a_i \partial b_{kl}} (a_i^\dagger + a_i)(b_{kl}^+ + b_{kl}) \\ &\approx \frac{\partial^2 \widehat{H}_I}{\partial a \partial b} (\sum_i a_i^\dagger + a_i) \hat{\Sigma}_x \end{aligned} \tag{A.31}$$

With this type of formulation, we may describe E1, E2 and M1 interactions on the same formal basis.

Appendix B:

We wish to explore the extension of our formulation to reactions where electron capture occurs before fusion. Our formulation will focus on the generic two-step reaction.

$$e + p + {}^{a}X \longrightarrow (n + \nu_e + {}^{a}X)_V \longleftrightarrow \nu_e + {}^{a+1}X \qquad (B.1)$$

This reaction is fundamentally more complicated than the fusion/beta reactions considered earlier since the neutron all neutrino and neutron energies must be included.

We begin by considering the microscopic problem of three initial particles (e, p and ${}^{a}X$). The Schrödinger equation which we shall adopt is written as

$$i\hbar\frac{\partial}{\partial t}\begin{bmatrix}\Psi_1\\ \Psi_2\\ \Psi_3\end{bmatrix} = \begin{bmatrix}H_1 & H_W & 0\\ H_W & H_2 & \widehat{H}_I\\ 0 & \widehat{H}_I & H_3\end{bmatrix}\begin{bmatrix}\Psi_1\\ \Psi_2\\ \Psi_3\end{bmatrix} + \widehat{H}_L\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\Psi_1\\ \Psi_2\\ \Psi_3\end{bmatrix} \qquad (B.2)$$

We have expanded out the creation and annihilation operator explicitly in this notation. The hamiltonian H_1 contains terms appropriate for the three initial particles (e, p and ${}^{a}X$) and the lattice, and Ψ_1 contains coordinates for the initial three particles and the lattice. The hamiltonians H_2 and H_3 contain terms appropriate for the three intermediate (and final) state particles ($n, \nu_e, {}^{a}X$), in the crude picture that ${}^{a+1}X$ is simply a bound state of the $n + {}^{a}X$ system. The collection of particles described by H_2 and H_3 are identical, and in this sense H_2 and H_3 are the same unless we find some way to distinguish between the spaces on which they operate. We shall employ projection operators P and Q which will give meaning to our separating H_2 and H_3. Specifically, we define

$$H_2 = PHP \qquad (B.3)$$

$$H_3 = QHQ \qquad (B.4)$$

where P projects out states in which the neutron is bound.

The electron capture occurs through the weak interaction, which is accounted for in the off-diagonal H_W in (B.2). The electromagnetic transitions which drive the coherent fusion process are in $\widehat{H}_I$. The hats in this equation refer to lattice operators. As before, the coupling between a fusion reaction and the lattice is assumed to be dominated by low order and low energy lattice transitions.

The generalization of the transformation to the dressed state picture is accomplished through a rotation similar to the one used in section III. The infinitesimal rotation operator of interest would be

$$\hat{R} = \frac{1}{2}\tan^{-1}\left[\frac{2}{H_2 - H_3}\widehat{H}_I\right]\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & i \\ 0 & -i & 0 \end{bmatrix} \qquad (B.5)$$

if $\widehat{H}_I$ commuted with $H_2 - H_3$. The transformed hamiltonian would then be approximately

$$\widehat{H}' = \begin{bmatrix} H_1 & H_W & 0 \\ H_W & H_2 & 0 \\ 0 & 0 & H_3 \end{bmatrix} + \widehat{H}_L \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$+ i\frac{1}{H_2 - H_3}\left[\widehat{H}_I, \widehat{H}_L\right]\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & i \\ 0 & -i & 0 \end{bmatrix} \qquad (B.6)$$

We would then extend our definition of the local dressed state interaction operator $\widehat{\Xi}_{kl}$ to be

$$\widehat{\Xi}_{kl} = i\frac{1}{H_2 - H_3}\left[\widehat{H}_I, \widehat{H}_L + \widehat{H}_{ext}\right] \qquad (B.7)$$

following equation (VII.11), and where we have included an external driving hamiltonian.

Acknowledgements

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Figure Captions

Figure 1: Schematic of two-step fusion/beta reaction $p+d \longleftrightarrow (^3He)_V \longrightarrow t+e^+ + \nu_e$. L stands for lattice in this diagram, and the electromagnetic exchange of many low energy photons is indicated here by a double photon line.

Figure 2: Two-step coherent beta/fusion reaction $p+d+e \longrightarrow (n+d+\nu_e)_V \longleftrightarrow t+\nu_e$.

Figure 3: Two-step coherent beta/fusion reaction $p+p+e \longrightarrow (n+p+\nu_e)_V \longleftrightarrow d+\nu_e$.

Figure 4: Example of a coherent fusion reaction involving electron capture by a deuteron.

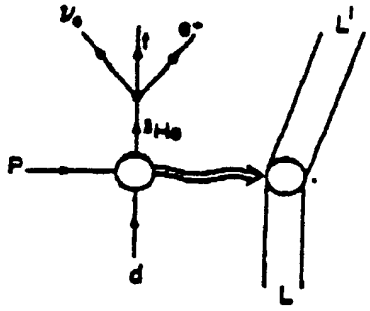

Fig. 1

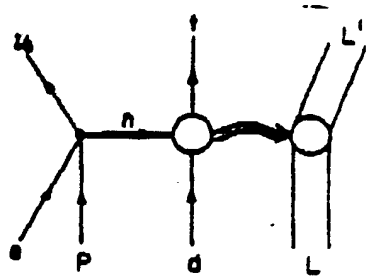

Fig. 2

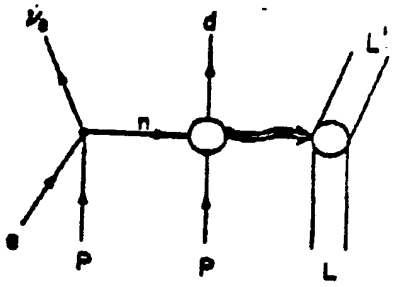

Fig. 3

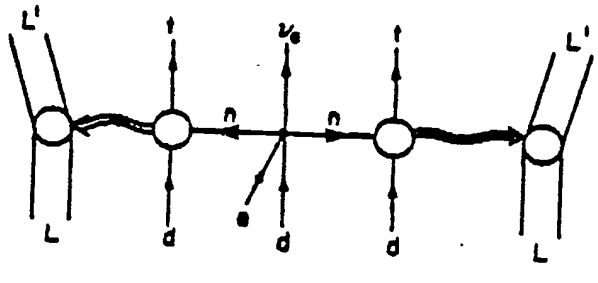

Fig. 4

Florence and Sam:

Sorry for taking so long to respond. I have been up to my gills in sorting out theory. I think that the new theory stuff is getting to be in very good shape - we'll see if my colleagues agree tomorrow.

I have attempted to provide by best guess from the theory as to what is required and what the applications are. The experimentalists think that there are no positrons, or at least not very many, in the cells producing tritium. This prompted me to go to capture-first models.

In the new scheme, alas, I cannot get ^3He. I should be able to turn ^3He into ^4He, but this is not of much use. Getting things going initially - I think that introducing some tritium would help (tritium production is exponential and I now think the tritium is better than deuterium is better than protons as a source of neutrons), and spin-polarizing (which is new and untried) should also make a difference. Magnetic fields should also help. I no longer think that fast particles help start things off.

Electronic transition laser materials are still in, but require production of an unstable isotope to drive. For example, $e + d + d + {}^{26}Mg \rightarrow (2n + \nu_e + d + {}^{26}Mg)_v \leftrightarrow \nu_e + t + {}^{27}Mg$ and the ^{27}Mg later decays producing decay products which could be made to drive elctronic transition lasers. The vibrational laser and maser claims are still physically possible, but would work through having either a very hot region supplying the optical phonons - I am not certain that we can get the fusion to drive the optical phonons directly (I doubt it), but it is something which in time I should be able to clarify.

I will call tomorrow. I hope that this is of some use.

-PH

According to current version of coherent theory, here is what is required:

(1) Source of virtual or off-shell neutrons: H, D, T are only possible sources. T is better than D, which is better than H. ($H = {}^1H, D = {}^2H, T = {}^3H$).

(2) Source of electrons at "high" density. Electron capture part is linear in electron density, and local electron density of $\sim 1/a_0^3$ is right ballpark ($a_0 = 0.529\mathring{A}$).

(3) Target nucleii for virtual neutron pickup: M1 pickup is allowed between any two ground state nucleii which have $\mid J_i - J_f \mid = 1/2$ and $\pi_i - \pi_f = 1$, where J_i and π_i are initial total angular momentum and parity, and J_f and π_f are final state total angular momentum and parity. E1 pickup has $\mid J_i - J_f \mid = \frac{1}{2}, \frac{3}{2}$ and $\pi_i - \pi_f = -1$. I believe that you were sent tables of the M1 and E1 isotopes. For example, ${}^1H$ can pick up a virtual neutron to make ${}^2H$ through M1 interaction.

(4) Source of coherence, or macroscopic polarizations. There are at least 3 distinct ways to do this.

a) Spin-polarize the electrons which are picked up. Some degree of polarization occurs in the presence of a magnetic field in Pd and Ti for example.

b) Spin-polarize the source of neutrons. (i.e. spin align the deuterium first)

c) Spin-polarize the target nucleons.

d) It may be possible to achieve electric polarization through alignment of quadrupole moments of the target nucleii.

[I believe that it is well known how to do this. Spin-aligned DT fusion experiments have been done. Nuclear spin alignment could be accomplished through selective excitation of hyperfine transitions using NMR techniques].

(5) Source of stimulation of coherent nuclear transitions.

a) For M1, M2, M3 etc. transitions, this implies macroscopic current flow, possibly in conjunction with magnetically permeable materials to guide and enhance the H-field. The only requirement of the field is that it stimulate the net emission or absorption of low energy photons from the coherent nucleii.

b) For E1, E2, E3 etc. transitions, this implies macroscopic excess charge density, possibly in conjunction with dielectric materials to increase local

field strength. Again, the only real requirement be that it cause absorption or emission from the coherent nucleii.

c) At high frequency, macroscopic magnetic fields give rise to induced electric fields, and time-changing electric fields give rise to induced magnetic fields. Hence excess surface charge can be used at high frequency to stimulate M1 transitions and so forth.

d) Radio-wave or microwave sources should be able to drive the coherent nuclear magnetic or electric dipoles. In principle, lasers can do it but the coherence size may be reduced.

(6) The above considerations are general for any coherent fusion device. Special applications might include:

a) Heat generation if the virtual neturon pick-up is to an unstable final state. For example, $^{26}Mg + n \rightarrow {}^{27}Mg$ where the final product has a decay time of 9.45 m. Also $^{7}Li + n \rightarrow {}^{8}Li$, where ^{8}Li decays in 0.844 sec. There are many such systems.

b) Heat generation may also be possible through stimulation of a macroscopic coherent magnetic or electric dipole in the presence of highly nonlinear media - for example, a highly stressed lattice. In this case there is the potential for multi-soft-photon emission. This applies both to current flow and M1, M2 etc. transitions (if the nonlinearity of the lattice affects the resistance) and excess charge (if the nonlinearity affects surface charge motion).

c) These systems should be strong sources of neutrinos.

d) Neutron pick-up should be assisted in E1 and M1 systems, and this allows production of isotopes in quantity for research applications. Of possible interest is ^{13}C, ^{134}Cs, ^{55}Fe *and* ^{59}Ni.

e) Neutron pick-up can be used on radioactive substances. The idea would be to add neutrons and increase the radioactivity (shorten the lifetime), such that some types of radioactive waste could be "neutralized". For example, ^{239}Pu can pick up a virtual neutron through M1 interaction.

f) (Use as a gamma source) Gamma emission should be possible through virtual neutron pick-up on high-Z elements. For example, ^{222}Rn has a

lifetime of 3.824 d. If it could pick up a neutron coherently, then it would decay faster (I think), and I am pretty sure that the decay sould involve a gamma pathway in a daughter.

g) (Use as a β source) β^+ and β^- emission are both in principle possible by selecting a final state with a β-decay path. This could provide an interesting source of β-radiation which can be at very high levels and controllable.

h) (Use as an x-ray source). The production of unstable isotopes (preferably short-lived at the second to minute level) will be accompanied by hard radiation (α, β, γ *etc.*). This radiation will be accompanied by secondary x-ray emission. A source based on this could be of tremendous use. The ^{26}Mg pickup to ^{27}Mg is my favorite candidate, and any element could serve as the UV or x-ray converter.

i) Driving chemical reactions: The production of unstable short lived isotopes would provide a source of nonthermal excitation which could be used to drive chemical reactions otherwise inhibited by an energy barrier. Cracking of N_2 near a coherent fusing surface containing ^{26}Mg is an example.

What is claimed is:

1. Fusion apparatus comprising:

fusible material; and

excitation apparatus for initiating coherent fusion of said material.

2. The apparatus of claim 1 further comprising a reactor vessel.

3. The apparatus of claim 1 wherein said excitation apparatus permits interaction of cosmic rays with said fusible material.

4. The apparatus of claim 1 wherein said excitation apparatus includes a source of α-particles.

5. The apparatus of claim 1 wherein said excitation apparatus creates non-linear effects in said reactor vessel.

6. The apparatus of claim 5 wherein said non-linear effects result from application of acoustical vibration.

7. The apparatus of claim 5 wherein said non-linear effects result from application of electrical fields.

8. The apparatus of claim 1 wherein said excitation apparatus is cosmic-ray permeable; and

further comprises a source of α-particles, a source of acoustical vibrations and a source of electric fields.

9. The apparatus of claim 1 wherein said fusible material includes hydrogen and deuterium whose relative abundance has been adjusted to optimize coherent fusion.

10. The apparatus of claim 8 wherein said fusible material includes hydrogen and deuterium whose relative abundance has been adjusted to optimize coherent fusion.

11. Fusion apparatus comprising:

fusible material; and

apparatus for coupling said fusible material to a quantized mode such that said coupling is strong enough to initiate coherent fusion.

12. The apparatus of claim 11 wherein said quantized mode is mechanical, electrical, magnetic, or composite.

13. The apparatus of claim 2 wherein said quantized mode has a wavelength.

14. The apparatus of claim 13 wherein said mode is generated by one or more oscillators.

15. The apparatus of claim 14 wherein said oscillator generates electromagnetic radiation.

16. The apparatus of claim 15 wherein said electromagnetic radiation is in the frequency range.

17. The apparatus of claim 14 wherein said oscillator includes a variable quality factor (Q) resonator.

18. The apparatus of claim 11 wherein said apparatus for coupling is an electrically conductive containment vessel.

19. The apparatus of claim 18 wherein said containment vessel has a radially symmetric geometry.

20. The apparatus of claim 19 wherein said geometry is a cylinder, sphere, or toroid.

21. The apparatus of claim 18 wherein said containment vessel is provided with external, radially disposed, rod-like projections for coupling said plasmon mode to said fusible material.

22. The apparatus of claim 21 wherein said rod-like projections are positioned on isopotential curves.

23. The apparatus of claim 21 wherein one or more of said projections is individually coupled to high quality factor (Q) resonators.

24. The apparatus of claim 11 wherein said fusible material includes hydrogen.

25. The apparatus of claim 11 wherein said fusible material includes deuterium.

26. The apparatus of claim 11 wherein said fusible material includes a mixture of hydrogen and deuterium.

27. The apparatus of claim 26 wherein said mixture is adjusted to optimize the coherent fusion rate.

28. The apparatus of claim 11 wherein said fusible material is a gas.

29. The apparatus of claim 11 wherein said fusible material is a liquid.

30. The apparatus of claim 11 wherein said fusible material is a solid.

31. The apparatus of claim 11 wherein said fusible material is maintained at a cryogenic temperature? to reduce P-D exchange?

32. The apparatus of claim 30 wherein said solid is a lattice.

33. The apparatus of claim 32 wherein said lattice is ice or a metal hydride.

34. The apparatus of claim 11 wherein said fusible material is provided with a proton source.

35. The apparatus of claim 11 wherein by-products of coherent fusion are removed from said containment vessel using a circulation loop.

36. The apparatus of claim 35 wherein said by-product is tritium.

37. The apparatus of claim 11 wherein usable power is extracted with a computer-controlled variable load electrically connected in series to said coupling apparatus.

38. The apparatus of claim 11 wherein usable power is extraced with a computer-controlled variable load electrically connected in parallel to said coupling apparatus.

39. The apparatus of claim 11 wherein said coherent fusion is stopped by selective introduction of a proton excess.

40. The apparatus of claim 11 wherein said coherent fusion is stopped by uncoupling said fusible material from said quantized mode.

41. The apparatus of claim 11 wherein said coupling is accomplished by radially polarizing insulating crystals.

42. The apparatus of claim 40 or 41 wherein microwaves are used to effect polarization.

43. Fusion apparatus comprising:

fusible material contained within an electrically conductive containment vessel provided with radially disposed rod-like projections which are electrically connected in series with an oscillator; and

a computer-controlled variable load to extract usable energy from coherent fusion.

44. The apparatus of claim 43 wherein said oscillator generates high frequency electromagnetic radiation.

45. The apparatus of claim 44 wherein said electromagnetic radiation is in the gigahertz to terahertz frequency range.

46. The apparatus of claim 44 wherein said oscillator includes a variable quality factor (Q) resonator.

47. The apparatus of claim 43 wherein said containment vessel has a radially symmetric geometry.

48. The apparatus of claim 47 wherein said geometry is a cylinder, sphere, or toroid.

49. The apparatus of claim 43 wherein said rod-like projections are positioned on isopotential curves.

50. The apparatus of claim 43 wherein one or more of said projections is individually coupled to high quality factor (Q) resonators.

51. The apparatus of claim 43 wherein said fusible material includes hydrogen.

52. The apparatus of claim 43 wherein said fusible material includes deuterium.

53. The apparatus of claim 43 wherein said fusible material includes a mixture of hydrogen and deuterium.

54. The apparatus of claim 43 wherein said mixture is adjusted to optimize the coherent fusion rate.

55. The apparatus of claim 43 wherein said fusible material is a gas.

56. The apparatus of claim 43 wherein said fusible material is a liquid.

57. The apparatus of claim 43 wherein said fusible material is a solid.

58. The apparatus of claim 43 wherein said fusible material is maintained at a cryogenic temperature.

59. The apparatus of claim 57 wherein said solid is a lattice.

60. The apparatus of claim 59 wherein said lattice is ice or a metal hydride.

61. The apparatus of claim 43 wherein said fusible material is provided with a proton source.

62. The apparatus of claim 43 wherein by-products of coherent fusion are removed from said containment vessel using a circulation loop.

63. The apparatus of claim 62 wherein said by-product is tritium.

64. The apparatus of claim 43 wherein said computer-controlled variable load is electrically connected in series or parallel to said coupling apparatus.

65. The apparatus of claim 43 wherein said coherent fusion is stopped by selective introduction of a proton excess.

66. The apparatus of claim 43 wherein said coherent fusion is stopped by disconnecting said oscillator from said containment vessel.

67. Fusion apparatus comprising:

fusible material contained within an electrically conductive containment vessel permeable to cosmic rays provided with radially disposed rod-like projections which are electrically connected in series with an oscillator; and

a computer-controlled variable load to extract usable energy from coherent fusion.

68. The apparatus of claim 67 further comprising an α-particle source.

69. The apparatus of claim 67 wherein said oscillator generates low frequency.

70. The apparatus of claim 69 wherein said electromagnetic radiation is in the frequency range.

71. The apparatus of claim 69 wherein said oscillator includes a variable quality factor (Q) resonator.

72. The apparatus of claim 67 wherein said containment vessel has a radially symmetric geometry.

73. The apparatus of claim 72 wherein said geometry is a cylinder, sphere, or toroid.

74. The apparatus of claim 67 wherein said rod-like projections are positioned on isopotential curves.

75. The apparatus of claim 67 wherein one or more of said projections is individually coupled to high quality factor (Q) resonators.

76. The apparatus of claim 67 wherein said fusible material includes hydrogen.

77. The apparatus of claim 67 wherein said fusible material includes deuterium.

78. The apparatus of claim 67 wherein said fusible material includes a mixture of hydrogen and deuterium.

79. The apparatus of claim 78 wherein said mixture is adjusted to optimize the coherent fusion rate.

80. The apparatus of claim 67 wherein said fusible material is a gas.

81. The apparatus of claim 67 wherein said fusible material is a liquid.

82. The apparatus of claim 67 wherein said fusible material is a solid.

83. The apparatus of claim 67 wherein said fusible material is maintained at a cryogenic temperature.

84. The apparatus of claim 82 wherein said solid is a lattice.

85. The apparatus of claim 84 wherein said lattice is ice or a metal hydride.

86. The apparatus of claim 67 wherein said fusible material is provided with a proton source.

87. The apparatus of claim 67 wherein by-products of coherent fusion are removed from said containment vessel using a circulation loop.

88. The apparatus of claim 87 wherein said by-product is tritium.

89. The apparatus of claim 67 wherein said computer-controlled variable load is electrically connected in series or parallel to said coupling apparatus.

90. The apparatus of claim 67 wherein said coherent fusion is stopped by selective introduction of a proton excess.

91. The apparatus of claim 67 wherein said coherent fusion is stopped by disconnecting said oscillator from said containment vessel.

92. The apparatus of claim 2, 18, 43 or 67 wherein said vessel consists of metal resistant to enhanced fission.

93. The apparatus of claim 92 wherein said metal is selected from a group consisting of metals having atomic numbers less than or equal to twenty-six.

94. The apparatus of claim 92 wherein said metal is Ti or Fe.

95. Fusion apparatus comprising:

fusible material contained within an insulating containment vessel surrounded by radially disposed polarizable crystals;

a microwave generator for polarization coupled to said crystals; and

an apparatus for extracting usable energy from coherent fusion.

96. The apparatus of claim 95 wherein said containment vessel has a radially symmetric geometry.

97. The apparatus of claim 96 wherein said geometry is a cylinder, sphere or toroid.

98. The apparatus of claim 95 wherein said fusible material includes hydrogen.

99. The apparatus of claim 95 wherein said fusible material includes deuterium.

100. The apparatus of claim 95 wherein said fusible material includes a mixture of hydrogen and deuterium.

101. The apparatus of claim 95 wherein said mixture is adjusted to optimize the coherent fusion rate.

102. The apparatus of claim 95 wherein said fusible material is a gas.

103. The apparatus of claim 95 wherein said fusible material is a liquid.

104. The apparatus of claim 95 wherein said fusible material is a solid.

105. The apparatus of claim 95 wherein said fusible material is maintained at a cryogenic temperature.

106. The apparatus of claim 95 wherein said solid is a lattice.

107. The apparatus of claim 95 wherein said lattice is ice or a metal hydride.

108. The apparatus of claim 95 wherein said fusible material is provided with a proton source.

109. The apparatus of claim 95 wherein by-products of coherent fusion are removed from said containment vessel using a circulation loop.

110. The apparatus of claim 95 wherein said by-product is tritium.

111. The apparatus of claim 95 wherein said coherent fusion is stopped by selective introduction of a proton excess.

112. The apparatus of claim 95 wherein said coherent fusion is stopped by uncoupling said microwave generator.

113. The apparatus of claim 95 wherein said vessel consists of material having a low atomic number.

114. The apparatus of claim 113 wherein said vessel is thin-walled.

115. The apparatus of claim 113 wherein said material is lithium hydride.

116. The apparatus of claim 95 wherein said apparatus for extracting usable energy consists of a metal positron trap which becomes heated as positrons are trapped.

117. The apparatus of claim 95 wherein said apparatus for extracting usable energy consists of thermally conductive mesh within said insulator for removal of heat buildup within said apparatus.

118. The apparatus of claim 95 wherein said apparatus is permeable to cosmic rays and includes an α-particle emitter to assist in initiation of coherent fusion.

119. The apparatus of claim 9, 10, 26, 27, 53, 54, 78, 79, 100 or 101 further comprising a selectively permeable membrane for adjustment of said mixture of hydrogen and deuterium.

120. The apparatus of claim 119 wherein said membrane consists of gold-coated palladium.

121. The apparatus of claim 1, 8, 10, 11, 43, 67, or 95 further comprising a neutron detector for monitoring the reaction rate.

122. The apparatus of claim 1, 8, 10, 11, 43, 67, or 95 further comprising an α-particle detector for monitoring enhanced α-decay caused by nuclear polarization.

123. A gas discharge laser comprising:

a fusion apparatus electrically connected in parallel with a variable resistance element for generating a potential between two electrodes in a chamber filled with a lasing medium; and

optical mirrors to define a laser cavity.

124. An electronic transition laser comprising: a pair of electrically excited fusion apparatuses electrically connected in series to an electronic transition laser material positioned within a laser cavity defined by optical mirrors.

125. An electronic transition laser comprising: an electrically excited fusion apparatus coupled via a filter material to an electronic transition laser material situated within a laser cavity defined by optical mirrors.

126. An electronic transition laser comprising: an electrically excited fusion apparatus coupled directly to an electronic transition laser material situated within a laser cavity defined by optical mirrors.

127. A vibrational transition laser or maser comprising:

a fusion apparatus directly coupled to a vibrational transition laser material situated within a laser cavity defined by optical mirrors.

128. A vibrational transition laser or maser comprising:

a fusion apparatus energetically coupled through a filter material to a vibrational transition laser or maser material which is situated in a laser cavity defined by optical mirrors.

129. Apparatus for promoting chemical reaction comprising: fusion host materials immersed in a fusible material contained in a vessel provided with an inlet for introduction of chemical reactants; and

apparatus for initiating coherent fusion.

130. Apparatus for promoting chemical reaction comprising: a fusion apparatus coupled directly to chemical reactants.

131. The apparatus of claim 129 or 130 wherein said chemical reaction is synthesis of nitrogen-containing compounds.

132. Apparatus for transmutation of elements comprising fusion host materials immersed in said elements; and

apparatus for initiation of coherent fusion.

133. Apparatus for transmutation of elements comprising a fusion apparatus coupled directly to elements to be transmuted.

134. The apparatus of claim 133 wherein said elements are high atomic number radioactive isotopes.

135. A neutron spectrometer comprising:

a fusion apparatus, a conduit for conveying neutrons from the fusion apparatus to an assembly further comprising:

a neutron intensity monitor, neutron energy controller, crystal specimen indexer, scattered neutron energy analyzer, and shielding.

136. A ^3He generator comprising:

a fusion apparatus; and

a vessel for collection of ^3He generated as a byproduct of a coherent fusion process in said fusion apparatus.

137. The apparatus of claim 1 wherein said excitation apparatus generates an ion beam which impinges upon said fusible material.

138. An amplifier comprising:

a fusion apparatus; and

a metal plate disposed at a distance from said fusion apparatus in a vacuum.

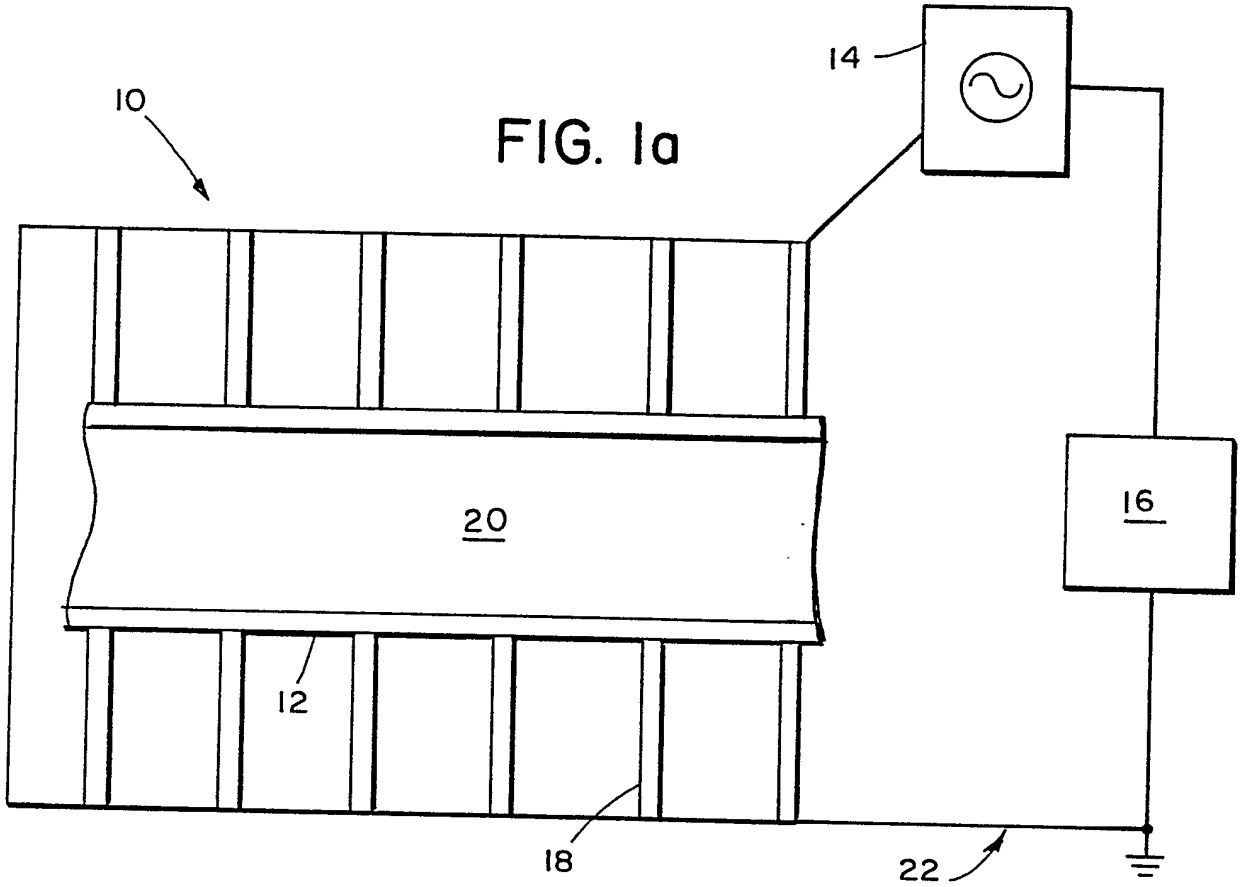

FIG. 1a

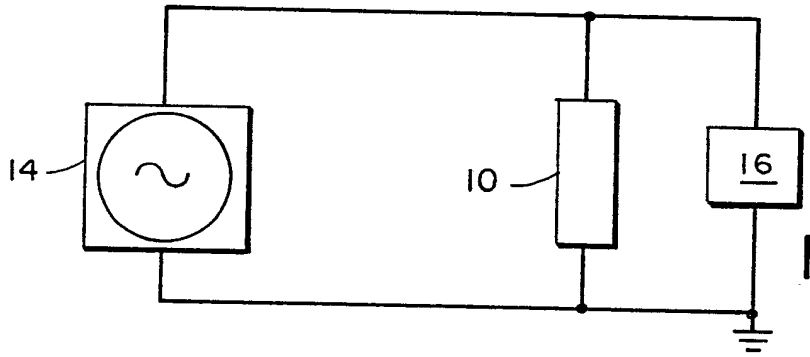

FIG. 1b

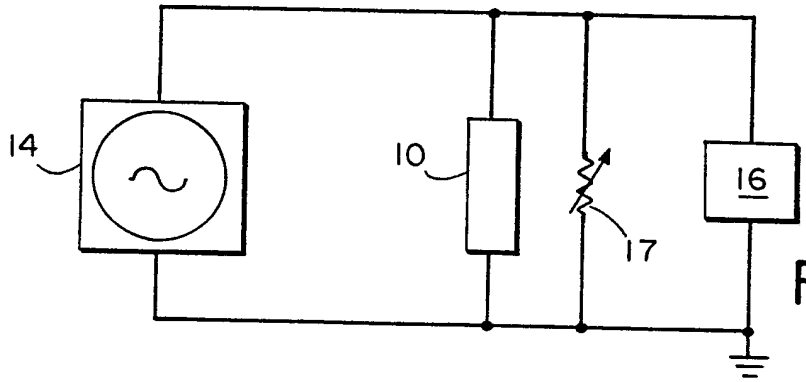

FIG. 1c

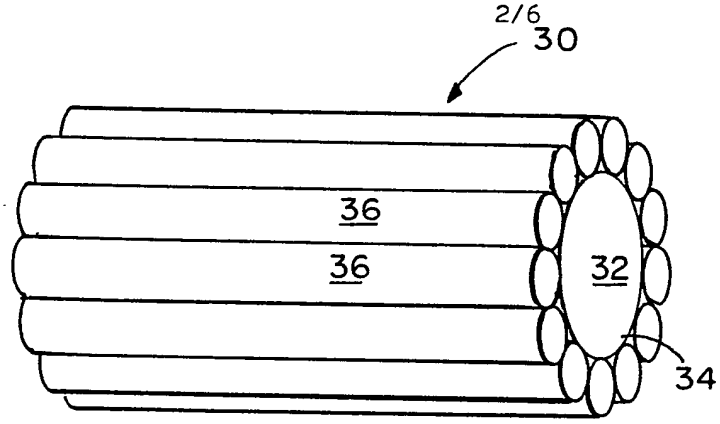

FIG. 2a

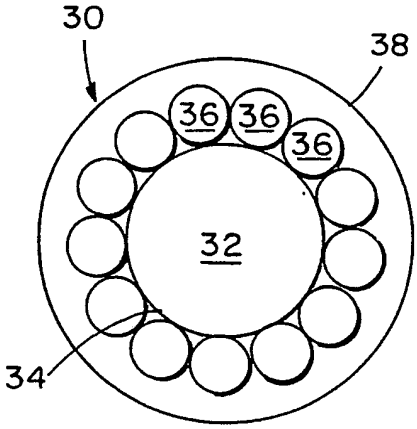

FIG. 2b

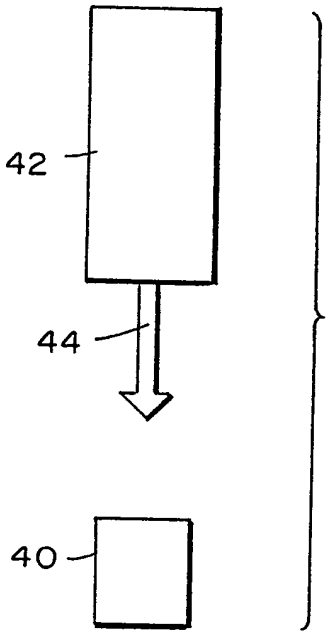

FIG. 3

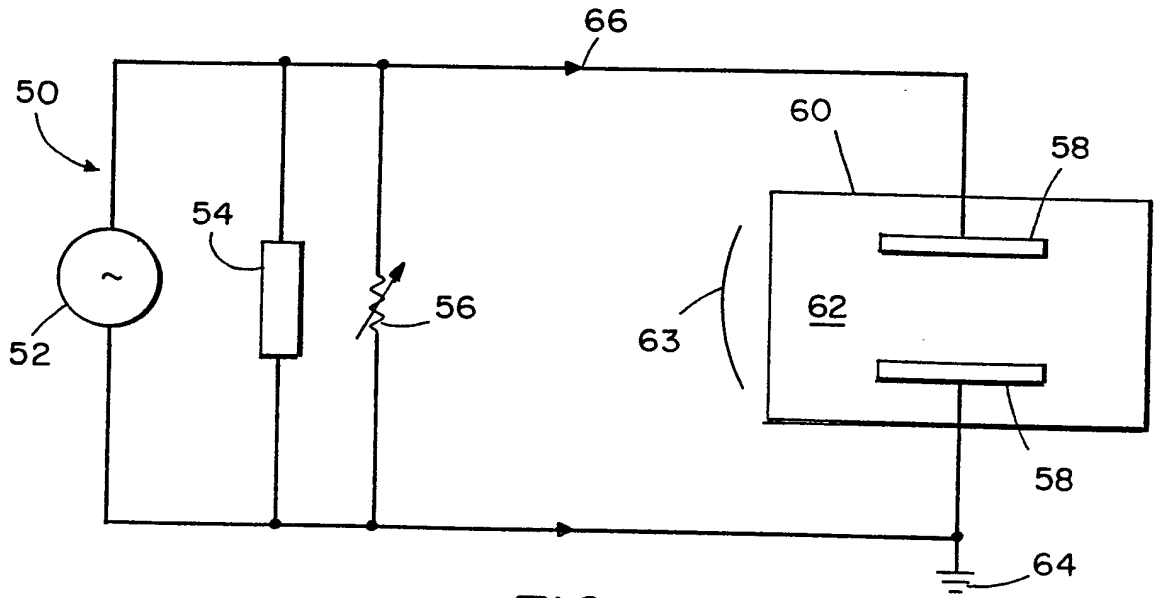

FIG. 4

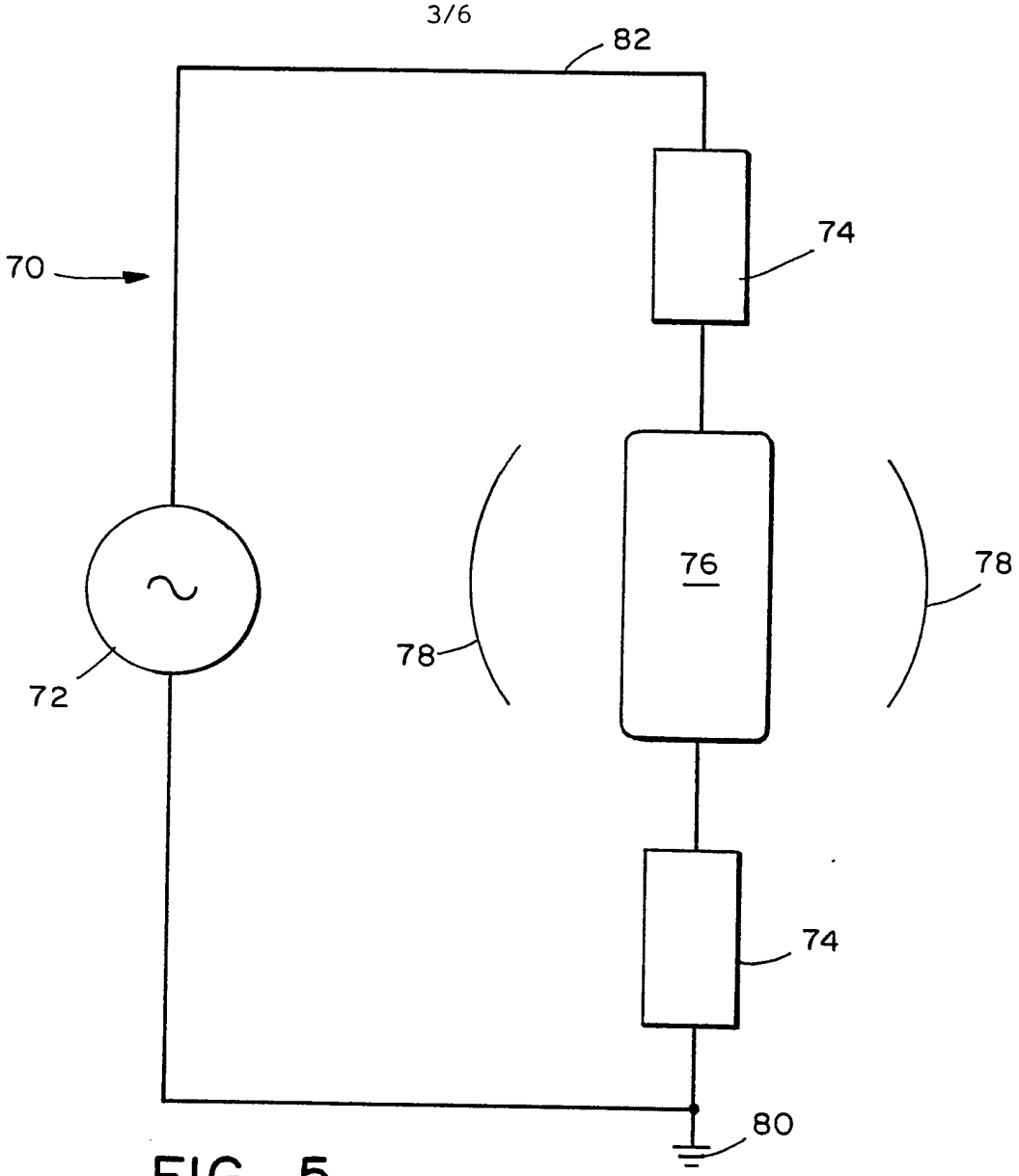

FIG. 5

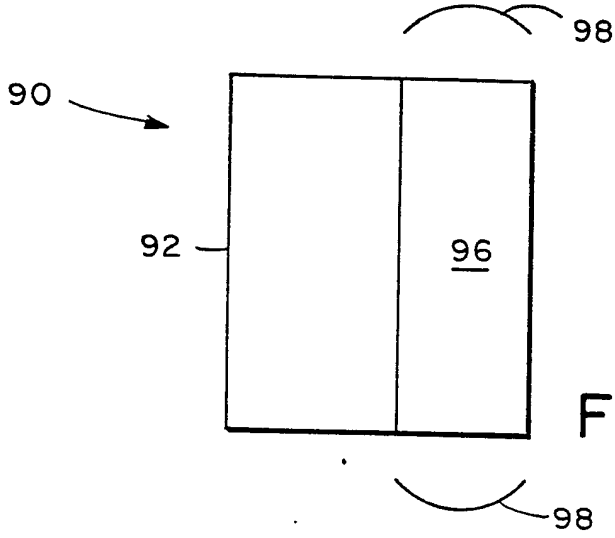

FIG. 6

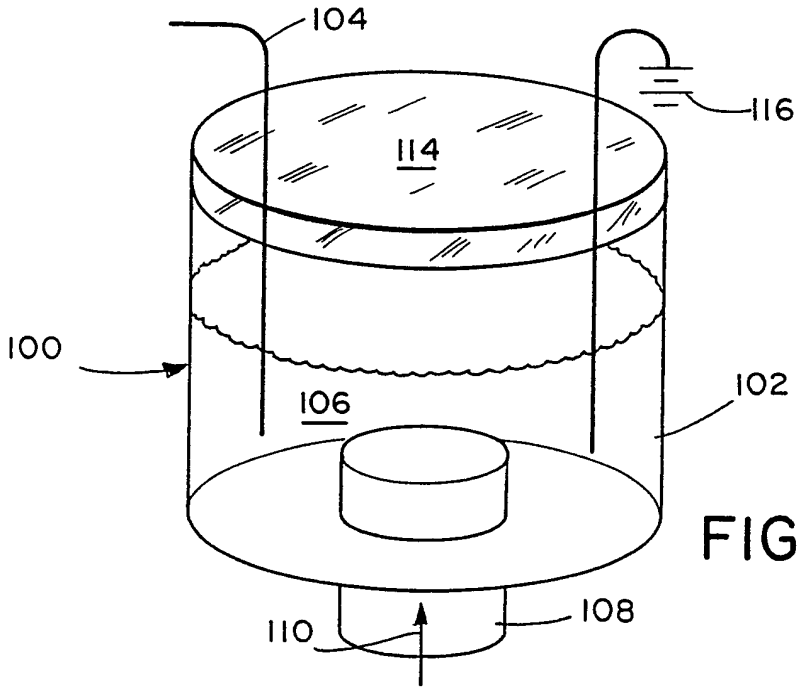

FIG. 7a

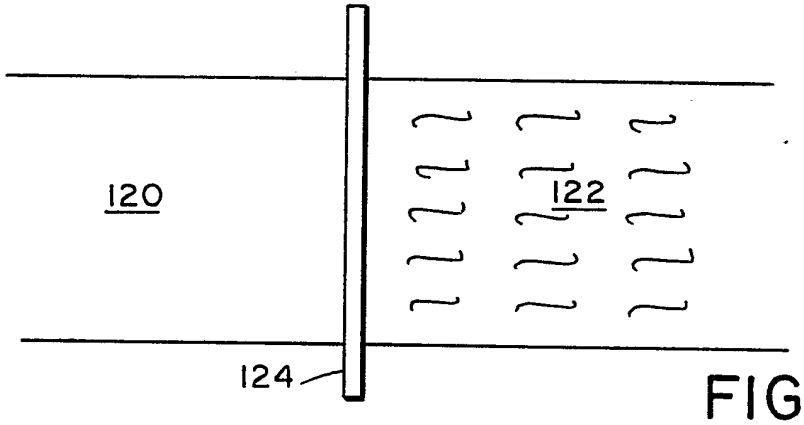

FIG. 7b

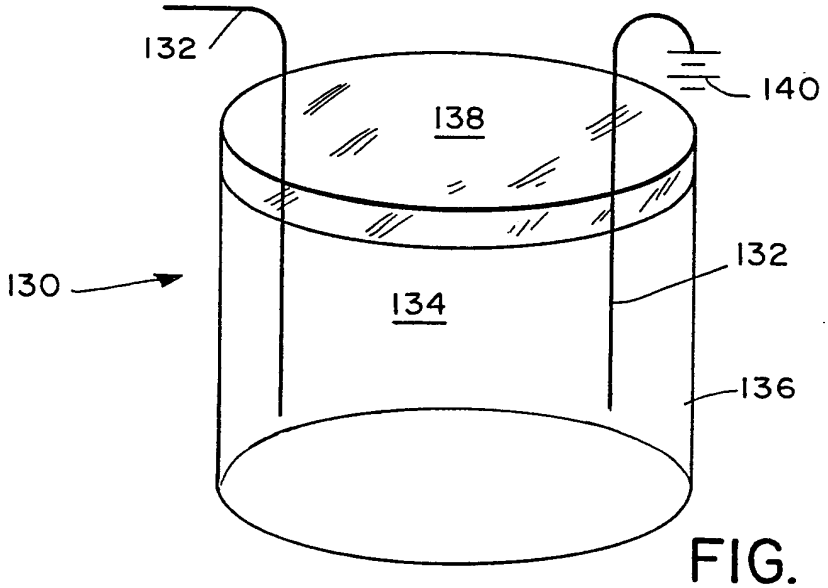

FIG. 8a

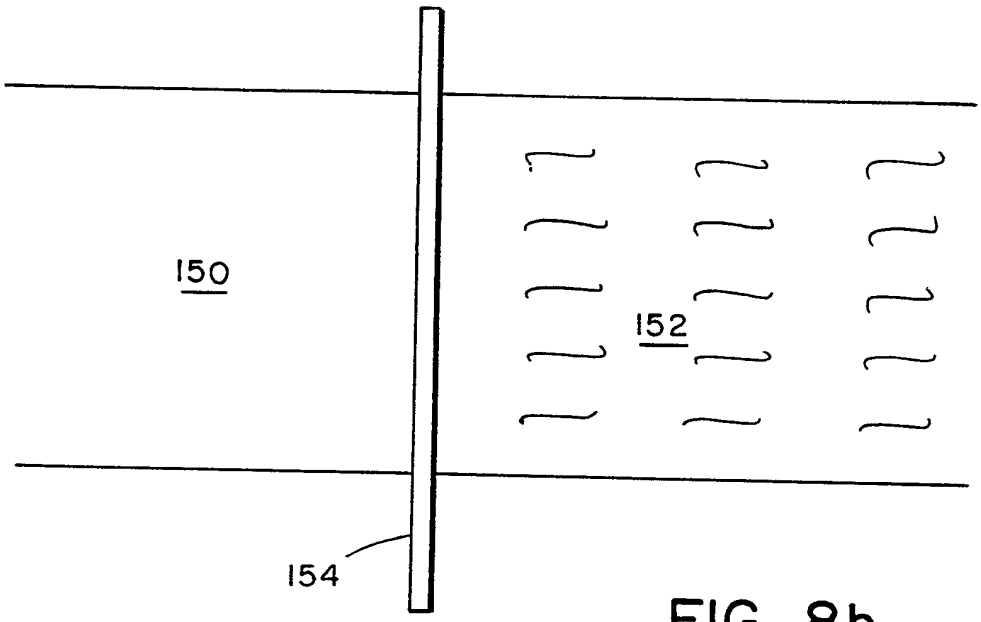

FIG. 8b

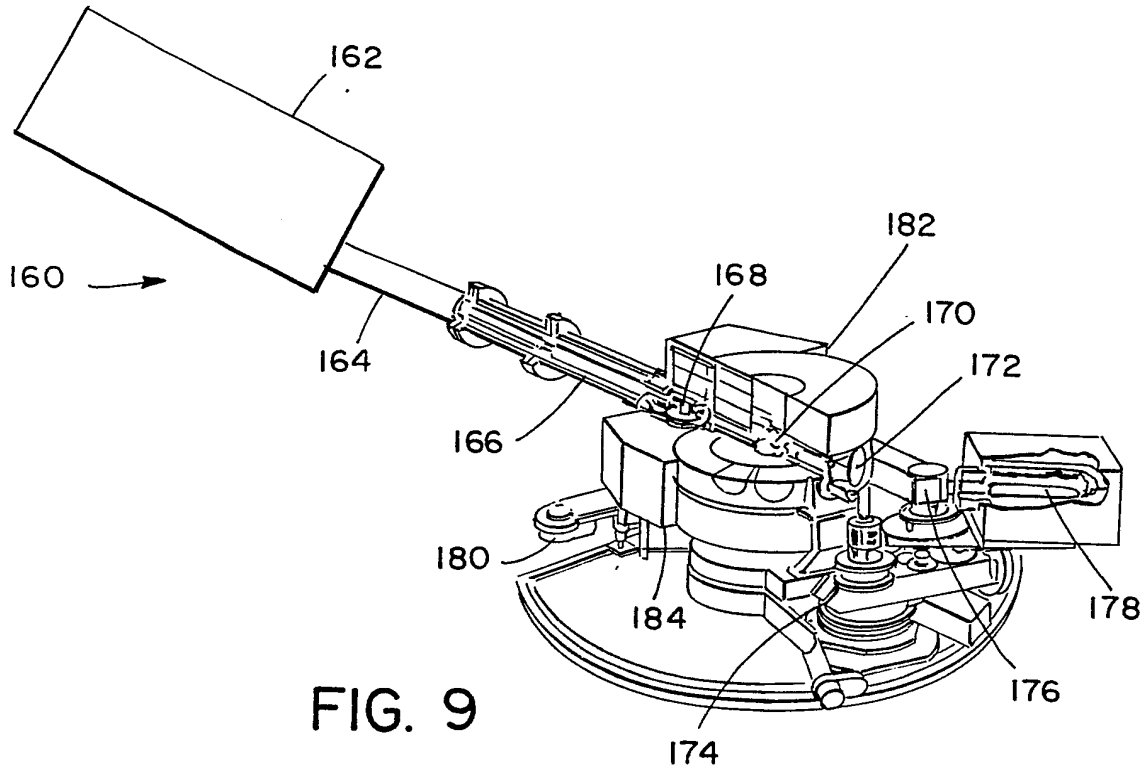

FIG. 9

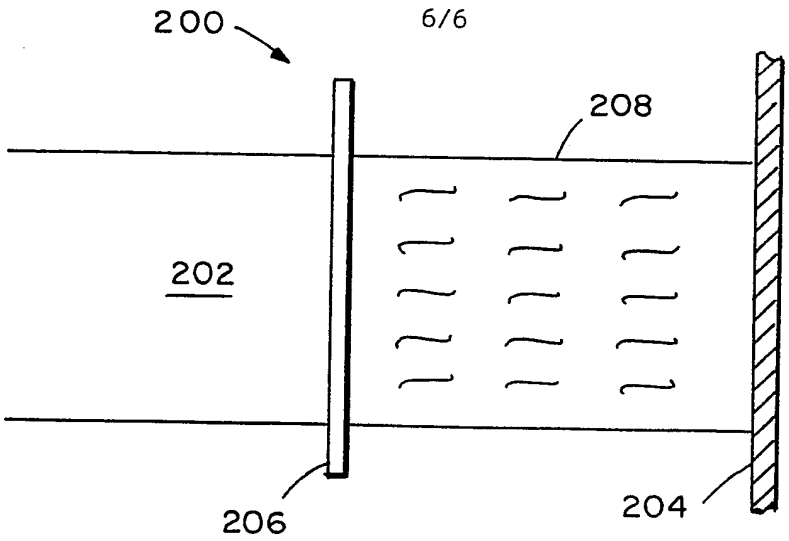

FIG. 12

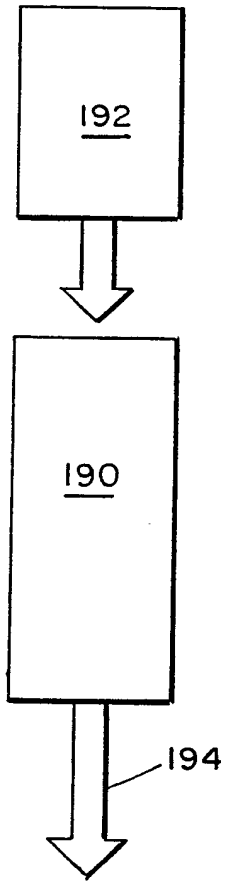

FIG. 10

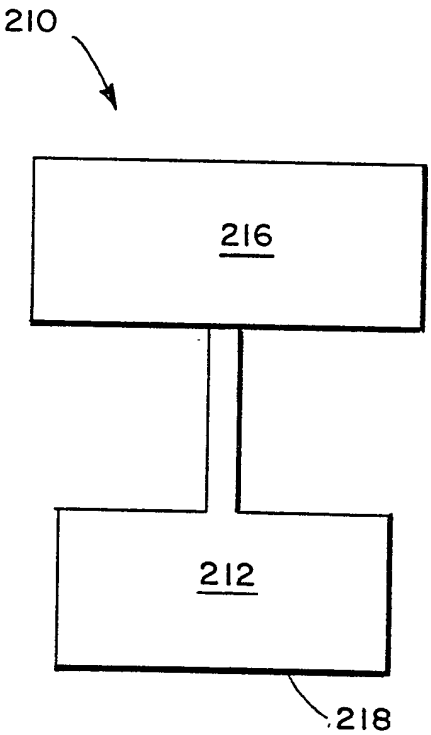

FIG. 11

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DOCUMENT-IDENTIFIER: WO 9013129 A2

TITLE: FUSION APPARATUS

PUBN-DATE: November 1, 1990

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APPL-DATE: April 6, 1990

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US44667489A (December 6, 1989)

INT-CL (IPC): G21C

EUR-CL (EPC): G21B001/02 , G21B003/00

US-CL-CURRENT: 376/100

ABSTRACT:

CHG DATE=19990617 STATUS=O>Fusion apparatuses for coupling fusible material to a quantized mode

to result in coherent fusion are provided. Method for optimization of reactor operation, control of the coherent fusion reaction and extraction of usable energy generated are provided.